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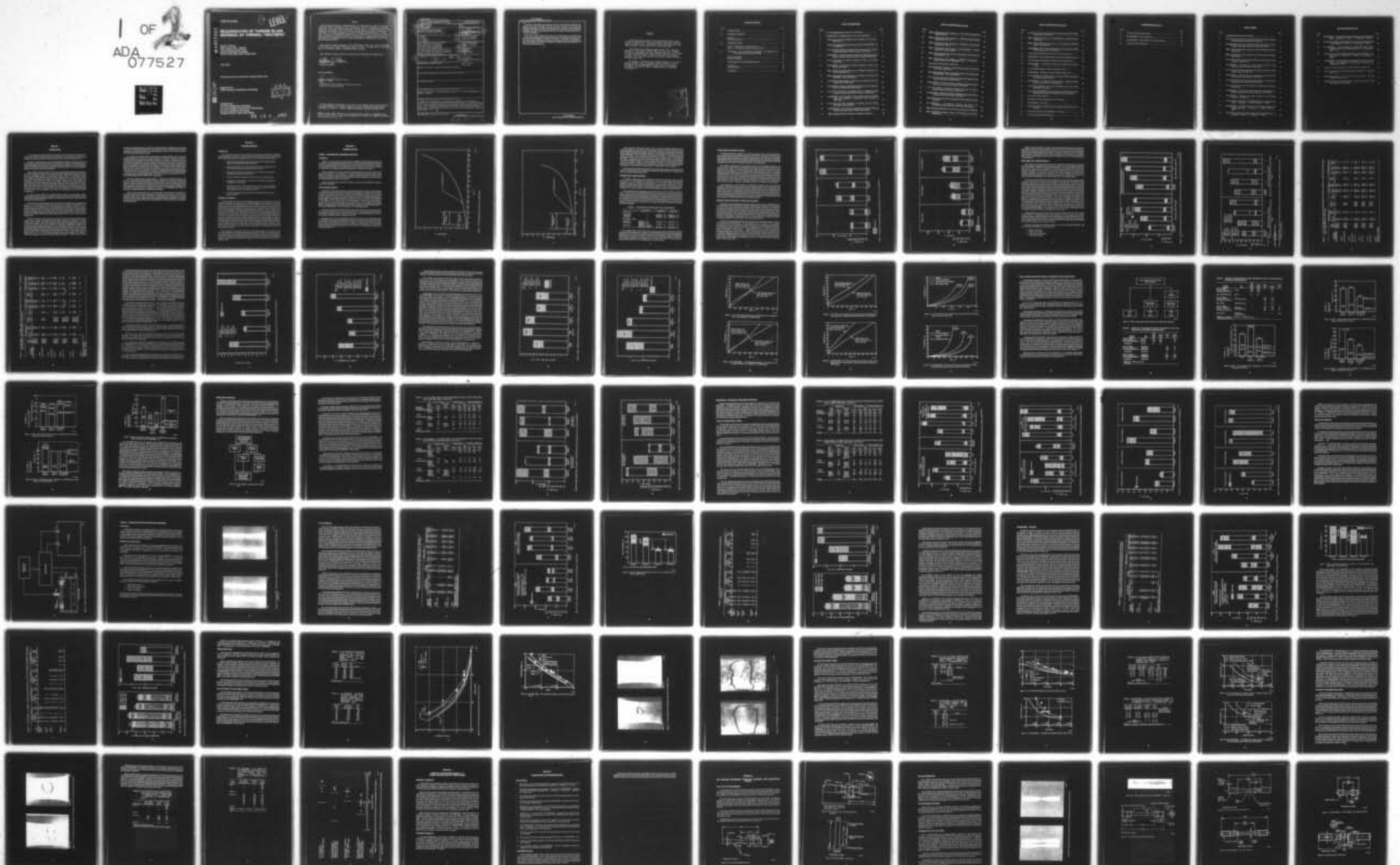

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REJUVENATION OF TURBINE BLADE MATERIAL BY THERMAL TREATMENT

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July 1979

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William T. O'Hara

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report describes a two phase program designed to investigate the feasibility of applying thermal treatments at some fraction of a turbine blade's life to heal accumulated fatigue and creep damage thereby extending useful blade life. Test evaluations were conducted on cast test bars of two nickel-base superalloys: conventionally cast (CC) IN 100 alloy and directionally solidified (DS) MAR-M200 + Hf.

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In Phase I, creep testing of cast specimens was used to select suitable rejuvenation heat treatments based upon recoverable creep life and strain. The effect of creep strain and subsequent rejuvenation on minimum mechanical property requirements and the maximum recoverable creep strain was also determined. In addition, the use of eddy current inspection was investigated as a method to provide specific NDI criteria for selection of components suitable for rejuvenation processing.

The Phase II effort included determinations of the effectiveness of rejuvenation heat treatments in recovering repeated creep strain damage and in recovering specific amounts of low-cycle and high-cycle fatigue life. In addition, the effects of rejuvenation heat treatments in recovering cumulative creep/fatigue strain damage was determined. Finally an assessment was made of the technical and economic feasibility for extending useful turbine blade life by rejuvenation thermal treatments.

FOREWORD

This Final Report covers all work performed under Contract F33615-76-C-5208 by the United Technologies Corporation, Pratt & Whitney Aircraft Group. Government Products Division, West Palm Beach, Florida, from 15 April 1976 to 15 October 1978.

This contract was initiated under Project 7351, "Metallic Materials," Task 735106, "Metals Behavior," Work Unit 735106B7. The work was performed under the technical direction of Mr Attwell M. Adair, and Mr William T. O'Hara of the Metals and Ceramics Division of the Air Force Materials Laboratory, Wright Patterson Air Force Base, Ohio.

Mr. Dennis C. Stewart was the Program Manager for the Pratt & Whitney Aircraft Group, Government Products Division, and was responsible for the management and execution of the program. Mr. Mike D. Ross and Mr. Gary T. Bennett served as principal investigators.

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SECTION I

INTRODUCTION

A cost reduction study conducted by W. Zavatkay in 1974 (Air Force Aero Propulsion Lab Contract No. F33657-73-C-0619) estimated that over 30% of total military gas turbine engine maintenance costs are attributed to repair and replacement of turbine blades and vanes.

Presently, visible damage is removed by blending (light grinding), recoating and, for some airfoils, weld repair. These operations are called refurbishment. In addition to visible damage, the airfoils suffer damage from creep and cyclic strains which are not detected by the nondestructive inspection (NDI) techniques presently employed. Operations designed to remove this damage are usually not included as a part of refurbishment.

Recent engines entering the USAF inventory have emphasized high performance characteristics achieved primarily through the use of advanced high strength, high temperature materials and high thrust/weight designs. The high-pressure turbine (HPT) and low-pressure turbine (LPT) blades of these engines are typically conventionally cast (CC) or directionally solidified (DS) nickel base superalloys, and these components experience the most severe combination of temperature, stress, and strain ranges in the engine. Allowable metal temperatures and estimated lives for turbine blades are set by design analysis of the material properties of the alloy, blade stage, engine model, and predicted mission. Generally, metal temperatures at critical airfoil sections have been set at 1500 to 1900°F. At these temperatures and the stress applied to HPT blades and the first two stages of LPT blades, relatively short lives of approximately 1000 to 3000 hr total time are generally found based on creep-rupture and thermal fatigue considerations.

In service, turbine blades are replaced based on NDI and creep (blade stretch) measurements. Major reductions in engine life-cycle costs could result from the ability to extend blade lifetimes through rejuvenation (restoration) of blade properties to their original levels after a suitable period of field service.

It is believed that both fatigue and creep lives of some nickel superalloys can be significantly extended by heat treatment. Although the metallurgical mechanisms responsible for this behavior are not fully understood, it is believed that selective thermal treatment of creep or fatigue damaged material will (1) solution and reprecipitate the microstructure to original or near original morphology, and (2) eliminate creep and cyclic strain damage through diffusion annealing processes. Rejuvenation treatments which heal microstructural and physical strain-damage could possibly extend turbine blade creep and failure limits to two or more times their present limits.

Repair procedures for military turbine components involving the bonding of corrosion/wear resistant tips to blades are presently being pursued along with evaluations of various refurbishment procedures concerning weld and/or coating repair of leading edge and tip erosion in field service blades. Current and potential turbine blade refurbishment procedures offer substantial savings potential in spare parts cost by extending useful blade life. However, creep and fatigue damage will still limit blade lives unless rejuvenation treatments can be utilized to restore original blade properties and ensure that repair procedures have not reduced remaining blade life. Development of rejuvenation processes which may extend turbine blade creep and fatigue limits to two or more times their present limits when combined with results of refurbishment programs will produce substantial lifetime extension of blades and vanes. Since recoating of existing hardware is cost effective even though baseline properties are not enhanced, it is clear that a feasibility demonstration of superalloy rejuvenation capability and its eventual application to gas turbine hardware can make a significant increase in the cost effectiveness of the turbine blade refurbishment process.

To validate the expected lifetime improvements in engine hardware and an expected significant reduction in inventory and spare parts cost, the extent of property recovery by rejuvenation heat treatments must be defined. Moreover, the limits of damage which can be recovered after prior exposure in fatigue and creep life must be determined since both properties are critical to successful blade operation. Based on the foregoing, this program was designed to evaluate the feasibility of turbine blade life extension by the recovery of creep and fatigue strain damage through suitable rejuvenation heat treatment of two different turbine blade casting alloys, one CC and one DC. The program was divided by alloy type into two tasks: Task I — Conventionally Cast (CC) IN 100 Alloy; and Task II — Directionally Solidified (DS) Mar-M200 + Hf Alloy. The CC IN 100 (PWA 658) is currently the Bill-of-Material in the F100-PW-100 3rd- and 4th-stage turbine blades; DS Mar-M200 + Hf (PWA 1422) is in use in the F100-PW-100 1st- and 2nd-stage blades and the TF30-P-100 1st-stage blade.

Each task is divided into two phases: Phase I — Rejuvenation Treatment Selection; and Phase II — Substantiation of Rejuvenation Treatment. In Phase I, creep testing of cast specimens was used to select suitable rejuvenation heat treatments based upon recoverable creep life and strain. The effect of creep strain and subsequent rejuvenation on minimum mechanical property requirements and the maximum recoverable creep strain was also investigated. In addition, the use of eddy current inspection was investigated as a method to provide specific NDI criteria for selection of components suitable for rejuvenation processing.

Phase II included determinations of the effectiveness of rejuvenation heat treatments in recovering repeated creep strain damage and in recovering specific amounts of low-cycle and high-cycle fatigue life. In addition, the effects of rejuvenation heat treatments in recovering cumulative creep or fatigue strain damage was investigated. Finally an assessment was made of the technical and economic feasibility for extending useful turbine blade life by rejuvenation thermal treatments.

SECTION II

PROGRAM OVERVIEW

OBJECTIVES

The overall objective of this 24-month program was to determine the feasibility of applying thermal treatments at some time during the life of a turbine blade to heat accumulated creep and/or fatigue damage thereby extending useful blade life. The specific objectives were:

1. Select a thermal treatment based on maximum recovery of creep properties generated at engine representative parameters.
2. Determine the effects of the selected rejuvenation heat treatment on the basic mechanical property requirements of the material.
3. Determine the maximum allowable creep strain which can be recovered by the selected rejuvenation heat treatment.
4. Evaluate the effects of multiple rejuvenation cycles on creep properties.
5. Investigate the effectiveness of rejuvenation of fatigue and cumulative creep/fatigue strain damage.
6. Correlate the results of NDI, including eddy current, with accumulated strain damage to provide a criterion to determine the fraction of life at which specimens can be successfully rejuvenated.
7. Perform all rejuvenation evaluations with two turbine blade alloys; one CC and the other DS.

TECHNICAL APPROACH

Although the results of this work will ultimately be applied to the rejuvenation of turbine airfoils, the feasibility of recovering creep and fatigue damage in these materials was conducted exclusively with cast and machined test bars. The selection of cast test bars rather than specimens machined from blades (MFB) was made for several reasons. First, most high-pressure turbine blades in today's military gas turbine engines are cast hollow to allow incorporation of internal cooling passages and baffles. Specimens machined from these airfoils would be quite small and would therefore yield significantly more data scatter than specimens machined from cast test bars. As a consequence, comparatively large numbers of specimens MFB would have to be tested to gain sufficient statistical confidence in the data. Second, an important feature of this work was to control the amount of strain damage imparted to each specimen so that the comparative effectiveness of each thermal rejuvenation cycle could be distinguished. In addition, other comparisons such as the maximum number of times specimens could be rejuvenated as well as the maximum amount of strain which could be recovered were also required. Clearly, specimens MFB would exhibit a wide range of internal damage dependent upon their unique service history and would not be useful for tests which require prior knowledge of the degree of damage initially present.

The introduction of internal creep strain and fatigue damage was conducted using parameters designed to simulate the temperature and stress environment experienced by engine run turbine blades. These specimens were tested and thermally treated in inert atmosphere to eliminate the necessity of repeated application and subsequent stripping of overlay aluminide coatings. This approach also simplified the conduct of nondestructive inspection following the prestrain cycles.

SECTION III

PROGRAM DETAILS

PHASE I — REJUVENATION TREATMENT SELECTION

Introduction

Phase I was concerned with the formulation of candidate thermal rejuvenation cycles and the selection, through mechanical testing, of the one cycle for each alloy found most effective to recover mechanical properties. Once the optimum cycle was selected, further work was conducted to confirm that rejuvenation of creep damage in test bars was actually occurring and not merely an improvement in mechanical properties resulting from a superior heat treatment.

Finally, mechanical tests were conducted to establish the maximum amount of creep strain damage recoverable by the application of thermal rejuvenation treatments. Eddy current inspection was applied to these specimens in an effort to determine whether the differing strain levels in each group of specimens could be distinguished thereby yielding an inspection criterion for detecting material in need of rejuvenation.

Details of test specimen procurement, inspection, machining, and qualification testing are presented in Appendix A.

Creep Parameter Selection

The selection of the creep temperature and stress parameters that were used in this program for identifying and evaluating the most promising heat treatments was based upon the need to simulate the temperatures and stresses to which turbine blading is exposed in service thereby providing a degree of microstructural strain damage to which the rejuvenation heat treatments could be applied. The parameters selected were 1650°F/40 ksi for CC IN 100 and 1800°F/28 ksi for DS Mar-M200 + Hf. The 1650 and 1800°F temperatures are temperatures that are experienced by the F100(3) CC IN 100 3rd-stage and DS Mar-M200 + Hf 1st-stage turbine blades, respectively. The 40 and 28 ksi stresses were designed to obtain creep prestrains and failures within a tractable period of time and still remain as close as possible to critical stresses for the CC IN 100 and DS Mar-M200 + Hf turbine blades at the testing temperatures.

The initial creep prestrain used for selection and initial evaluation of the rejuvenation heat treatments for both alloys was 1.0% strain. The selection of 1.0% prestrain was made because it was significant enough to produce some degree of microstructural strain damage but not so severe as to produce irreversible surface cracking in either alloy.

Representative creeps curves obtained by testing CC IN 100 specimens at 1650°F/40 ksi and DS Mar-M200 + Hf specimens at 1800°F/28 ksi are plotted in Figures 1 and 2, respectively. These plots illustrate the occurrence and duration of the primary, secondary, and tertiary creep modes for these conditions of temperature and stress. In addition, it is revealed that 1.0% creep strain extends well into the tertiary creep range for CC IN 100 and into the beginning of tertiary creep for DS Mar-M200 + Hf.

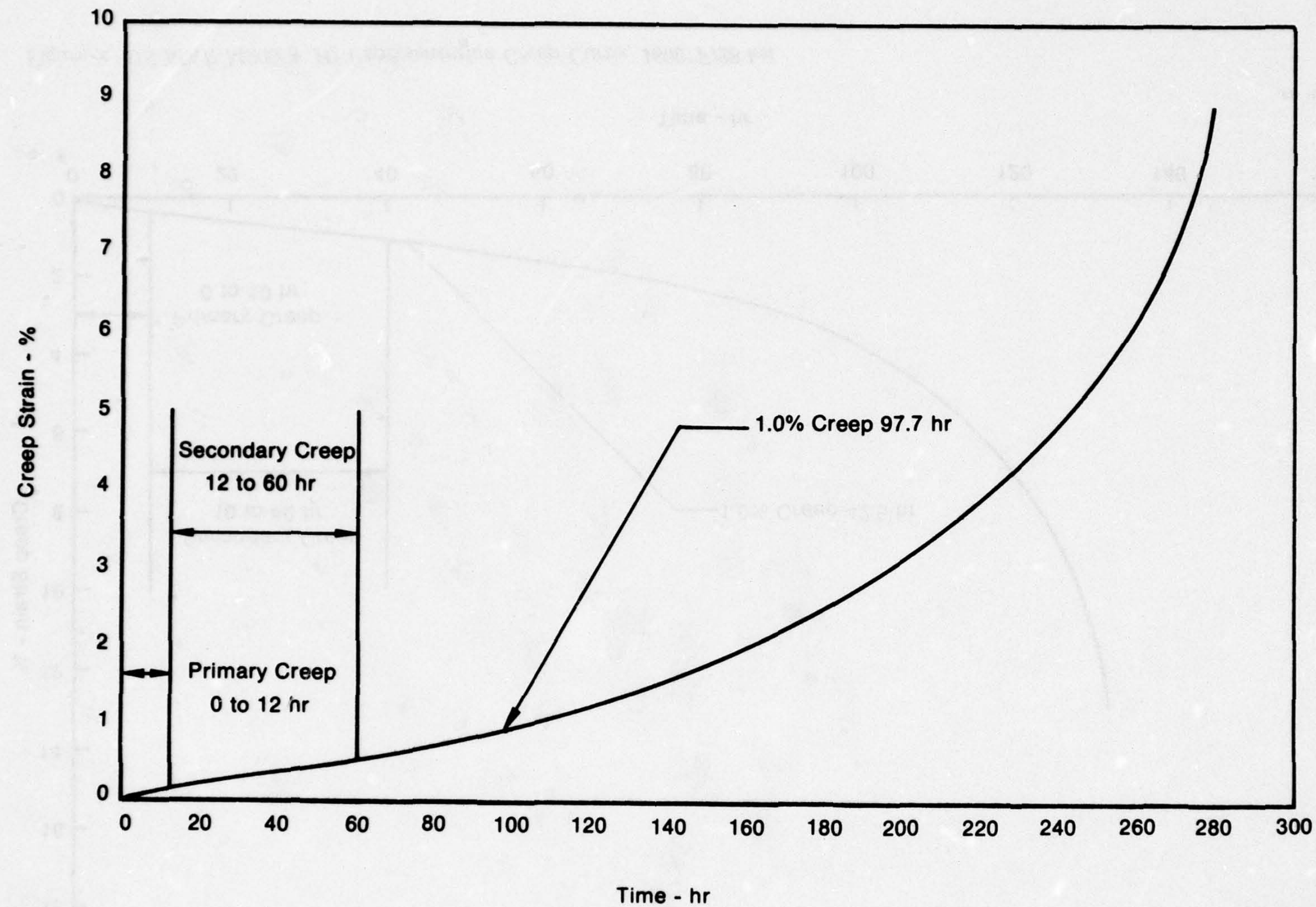

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Figure 1. CC IN 100 Representative Creep Curve, 1650°F/40 ksi

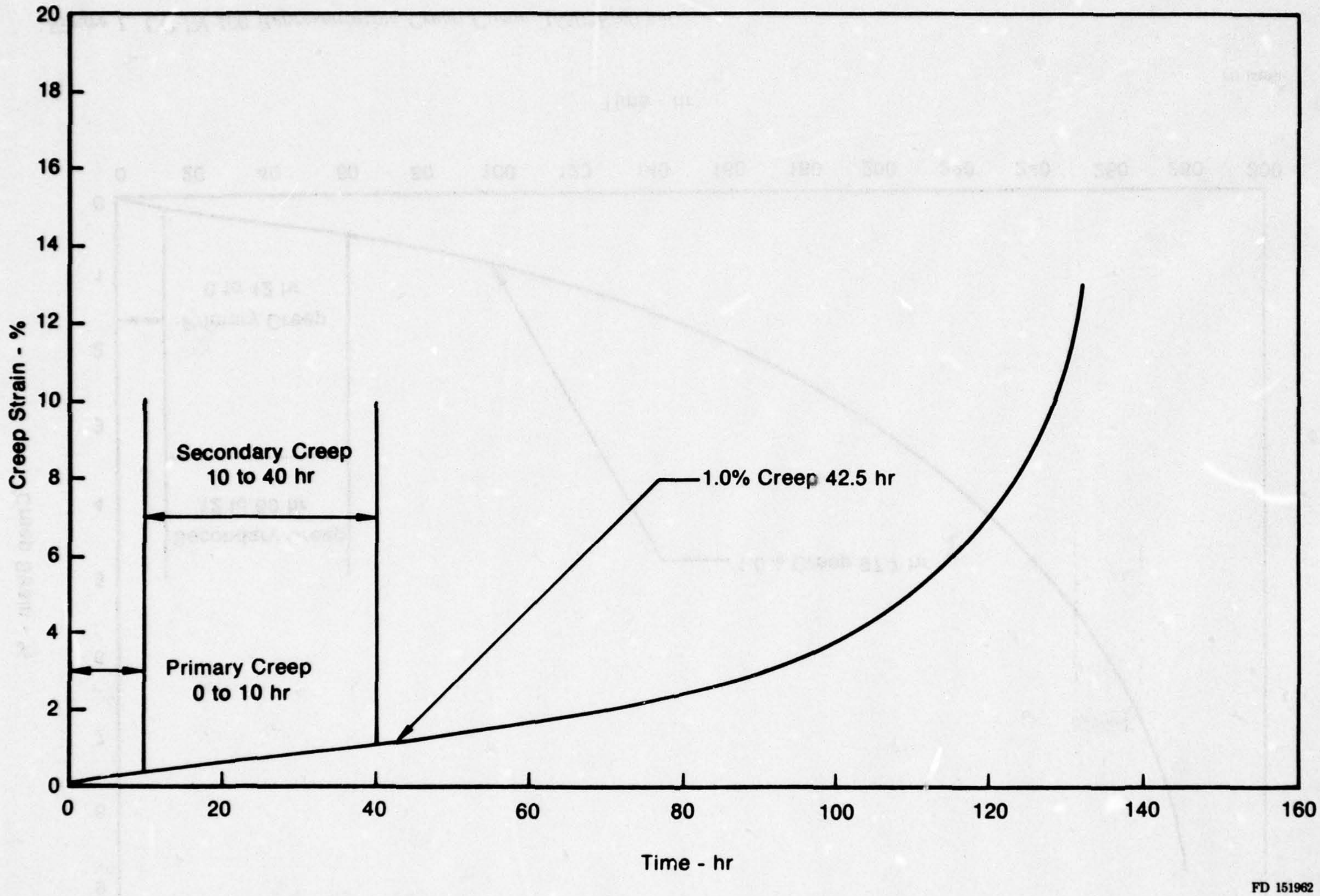

Figure 2. DS MAR-M200 + Hf Representative Creep Curve, 1800°F/28 ksi

Using specimens strained into tertiary creep to evaluate candidate rejuvenation heat treatments appears to be in conflict with the assumption that thermal rejuvenation treatments should be applied only within secondary creep limits to avoid creep strain damage in the form of large cavitation voids and microcracking. However, the predominant creep mode for CC IN 100 and DS Mar-M200 + Hf at the subject temperatures and stresses is in the tertiary range and makes up over 60% of the total rupture life for each alloy. Therefore, while CC IN 100 and DS Mar-M200 + Hf specimens would have experienced a degree of tertiary creep, it was anticipated that cavitation damage would be minimal or nonexistent and thermal rejuvenation treatments could still be effective. In addition, it was desirable to determine, by testing, whether thermal rejuvenation of creep is indeed limited to intermediate, secondary creep or whether significant rejuvenation can be attained from prestraining at or within tertiary creep boundaries.

The selection of the prestrain parameters for determining the maximum recoverable creep strain for each rejuvenation heat treatment was based on the initial Phase I test evaluations and will be more appropriately discussed later.

Candidate Heat Treatment Selection

The ability of rejuvenation heat treatments to restore creep properties relies on several factors: First, the heat treatment should solution the gamma prime phase coarsened and elongated by the 1.0% prestrain and reprecipitate it in a normal cuboidal form. Second, undesirable carbide phases should be solutioned and, during the aging cycle, reform into more desirable carbides. Third, cavitation damage which generally occurs at brittle grain boundary carbides and by vacancy diffusion, must be sintered closed by thermally activated diffusion.

Three rejuvenation heat treatments were selected for use with CC IN 100 and are listed in Table 1. The first was the standard PWA 658 coat and age cycle while the remaining two employed feasible coating cycles with progressively higher temperatures in an effort to resolution as much gamma prime and carbide phases as possible and to increase the diffusivity relative to the sintering of stress induced voids. High temperature solution treatments were avoided with CC IN 100 because past experience has shown that the resulting agglomeration of gamma prime particles and the formation of gamma prime envelopes along grain boundaries can degrade mechanical properties.

TABLE 1. CANDIDATE REJUVENATION HEAT TREATMENTS

	Solution Cycle	*Coating Cycle*	*Aging Cycle*
CC IN 100 Alloy			
Heat Treat A	—	1975°F/8 hr — AC	1600°F/12 hr — AC
Heat Treat B	—	2025°F/4 hr — AC	1600°F/12 hr — AC
Heat Treat C	—	2100°F/2 hr — AC	1700°F/16 hr — AC
DS Mar-M200 + Hf Alloy			
Heat Treat A	2200°F/4 hr — AC	1975°F/4 hr — AC	1600°F/32 hr — AC
Heat Treat B	2200°F/10 hr — AC+ 2250°F/4 hr — AC	1975°F/4 hr — AC	1600°F/32 hr — AC
Heat Treat C	2200°F/10 hr — Fast AC+ 2250°F/4 hr — Fast AC	1975°F/4 hr — AC	1600°F/32 hr — AC

The standard PWA 1422 solution, coat, and age cycle plus two additional thermal rejuvenation heat treatments were selected for DS Mar-M200 exhibits better heat treatment response than CC IN 100, the candidate rejuvenation heat treatments employed significantly higher solution temperatures than those used for CC IN 100. Moreover, duplex heat treatments were employed in an effort to homogenize the alloy and raise the incipient melting temperature (approximately 2230°F) prior to the application of a 2250°F solution.

Creep Prestrain and Retest Procedure

All Phase I evaluations required the use of test specimens with an initial predetermined creep strain produced at the selected parameters for each alloy. The prestrain tests to provide these specimens were performed as a normal creep-rupture test except that upon reaching the predetermined strain level, the test was discontinued by shutting down the furnace and allowing the specimen to cool under load. Upon cooling to 1000°F, the load was removed and the specimen transferred from the furnace for subsequent cooling to room temperature.

The delayed unloading and initial furnace cooling of the prestrained specimens was necessary for two reasons. First, the maintained load prevented dimensional distortion of the specimen which could occur by eliminating the load at high temperatures. Second, the forced furnace cool was considered to be more representative of the thermal environment of a turbine blade and provide a greater degree of test control. For both alloy tests the time to reach 1000°F was approximately 2 hr, and since the specimens were maintained under load during this period a small amount of creep strain was added to each specimen during the cooldown cycle. This additional induced creep strain ranged from 0.002 to 0.020% strain for all specimens tested. These small amounts of creep strain were considered insignificant compared to the predetermined strain levels and were not, therefore, incorporated into any of the creep strain data analyses.

After application of creep prestrains, all specimens, depending upon the task being performed, were either directly retested to failure (interrupted test) or were rejuvenation heat treated prior to the retest. In either case the retest to failure of a specimen was conducted as a new original test and not as a continuation of the interrupted prestrain test. To accomplish this, the reduced cross section of each prestrained specimen was determined and used to recalculate the creep loading need for the appropriate stress level. By this means, the retesting of specimens was effectively standardized and provided a more meaningful comparison to be made between the creep properties of baseline and thermally rejuvenated specimens.

Baseline Testing and the Effect of Creep Test Interruption

Continuous and interrupted creep tests were conducted on CC IN 100 at 1650°F/40 ksi and on DS Mar-M200 + Hf at 1800°F/28 ksi to establish a baseline data base against which the results of testing with thermally rejuvenated specimens could be compared. Since the tests conducted with rejuvenated specimens were by necessity interrupted, similar baseline testing was necessary to distinguish any effects the test interruption may have had on creep properties and to assure that valid comparisons could be made between rejuvenated creep properties and baseline creep properties for both alloys. The interrupted baseline tests were performed by prestrain testing CC IN 100 and DS Mar-M200 + Hf specimens to 1.0% at their respective test parameters and then retesting the specimens to failure without rejuvenation heat treatment.

Continuous and interrupted baseline results are plotted as bar graphs in Figure 3 for CC IN 100 and Figure 4 for DS Mar-M200 + Hf. The prestrain (0.0 to 1.0%) retest (1.0% to rupture) components and the total creep results are shown along with the corresponding scatterband for each test group in order to provide a more effective comparison. For CC IN 100 the total rupture life increased from 257.1 to 265.6 hr and total creep strain from 7.54 to 7.79% for the interrupted baseline as compared to the continuous baseline. The scatterbands for both continuous and interrupted baseline tests, however, indicate that both types of tests are essentially the same with no significant differences between the total or component results. Figure 3 shows that total rupture life for DS Mar-M200 + Hf decreased from 126.3 to 123.8 hr for continuous tests versus interrupted tests while creep strain increased from 15.4 to 17.9%. Again, however, all results are within a similar scatter band.

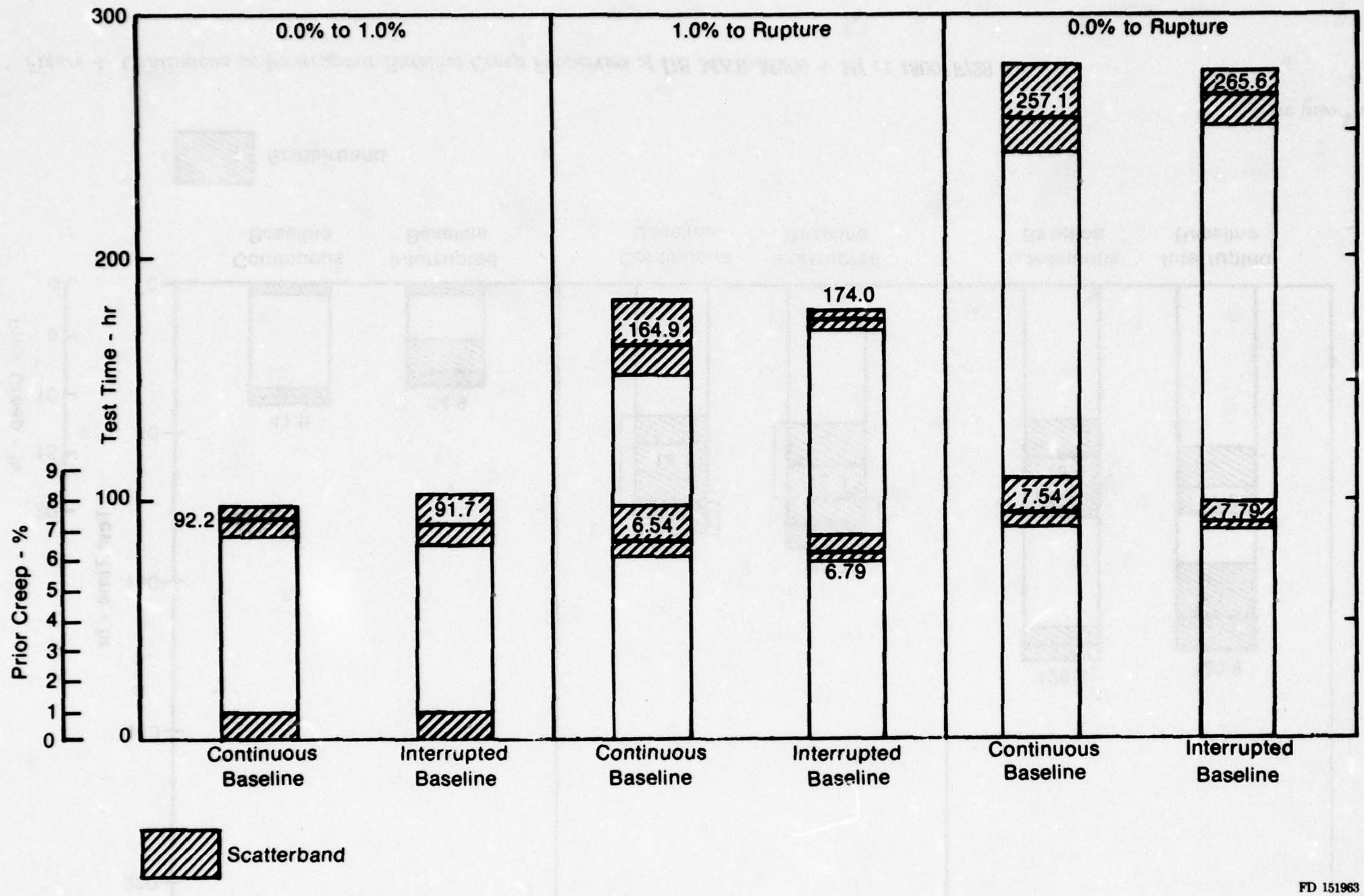

Figure 3. Continuous vs Interrupted Baseline Creep Properties of CC IN 100 at 1650°F/40 ksi

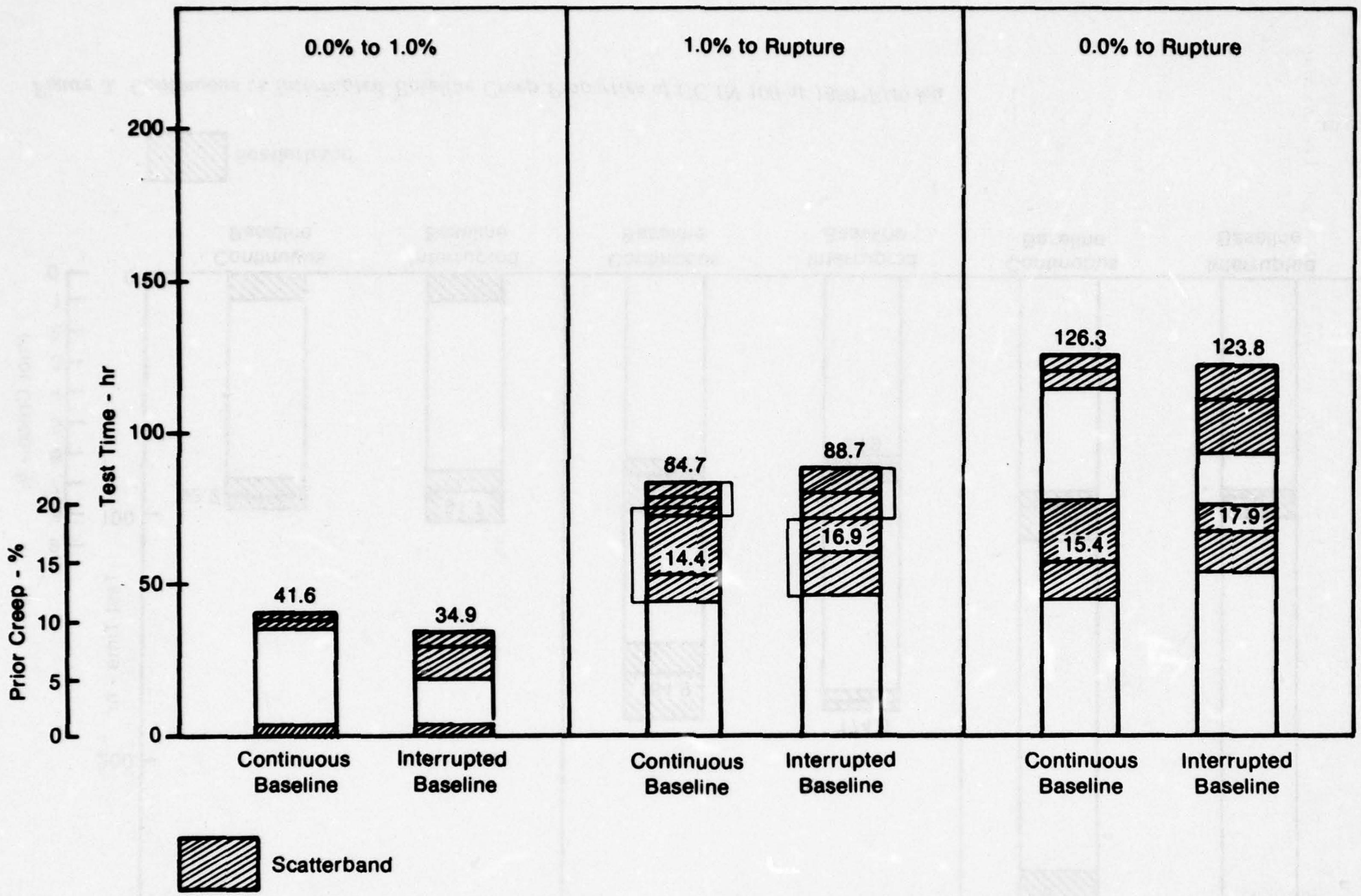

Figure 4. Continuous vs Interrupted Baseline Creep Properties of DS MAR-M200 + Hf at 1800°F/28 ksi

Based on these observations, the effect on total rupture life and creep strain resulting from interruption of the creep test was considered minimal for both CC IN 100 and DS Mar-M200 + Hf test specimens when compared to the results of continuous creep tests. The data accumulated from both test methods was therefore averaged to provide an increased data base for baseline creep properties at 1650°F/40 ksi are 261.4 hr rupture life and 7.67% creep strain. The DS Mar-M200 + Hf average baseline properties are 125.2 hr rupture life and 16.4% creep strain for tests at 1800°F/28 ksi.

Rejuvenation Heat Treatment Selection

The selection of the optimum rejuvenation heat treatment was determined by comparing the retest properties of prestrained specimens rejuvenated by each of the candidate cycles shown previously in Table 1. After CC IN 100 and DS Mar-M200 + Hf specimens were 1.0% prestrain tested at their respective creep parameters, each was subjected to 10X visual and fluorescent penetrant inspections to ensure that no surface defects were generated by the prestrain test. Following inspection, the specimens were given the various candidate rejuvenation heat treatments and retested to failure. The resulting rupture life, prior creep strain, and creep curve behavior was then compared with the corresponding results of the baseline testing.

The data have been plotted in the form of bar graphs with indicated scatterbands as shown in Figures 5 and 6 for CC IN 100 and DS Mar-M200 + Hf, respectively. This method of data presentation permits direct comparison of rupture properties as a function of the heat treatments received by each group of specimens. Moreover, each bar graph has been divided into a left and a right section. The left side represents rupture life and prior creep elongation remaining after the 1.0% prestrain while the right side includes the prestrain and represents total rupture properties. This makes it possible to distinguish between heat treatments which actually recovered rupture properties lost during the prestrain and those that may only represent superior heat treatments for the properties being tested. For example, examination of the left side of the bar graphs reveals that, for both CC IN 100 and DS Mar-M200 + Hf, each of the candidate rejuvenation heat treatments produced some degree of property recovery when compared to the baseline tests. However, the right side, which represents total rupture properties, reveals that specimens with rejuvenation heat treatments exhibited superior properties when compared to the baseline. Since it is impossible to recover more than 100% of properties lost due to the 1.0% prestrain, then it must be concluded that while some degree of rejuvenation may indeed be occurring, the rejuvenation heat treatments must also be improving the 1650 and 1800°F rutpure properties of CC IN 100 and DS Mar-M200 + Hf, respectively. The actual extent of rejuvenation will be investigated by testing which will be discussed later in this report.

The bar graphs were constructed from the data shown in Tables 2 and 3 for CC IN 100 and DS Mar-M200 + Hf, respectively. Each table contains all the creep rupture data including continuous baseline, interrupted baseline, and the three groups of specimens prestrained to 1.0%, rejuvenation heat treated, and retested to failure. The baseline data presented in the bar graphs is the averaged results of both continuous and interrupted baseline tests, both test types having been determined equivalent in the previous section.

Selection of the optimum candidate rejuvenation cycle for IN 100 and DS Mar-M200 + Hf was based upon the following four considerations:

1. Rupture life recovery
2. Time to 1.0% creep
3. Prior creep strain recovery
4. Creep curve behavior.

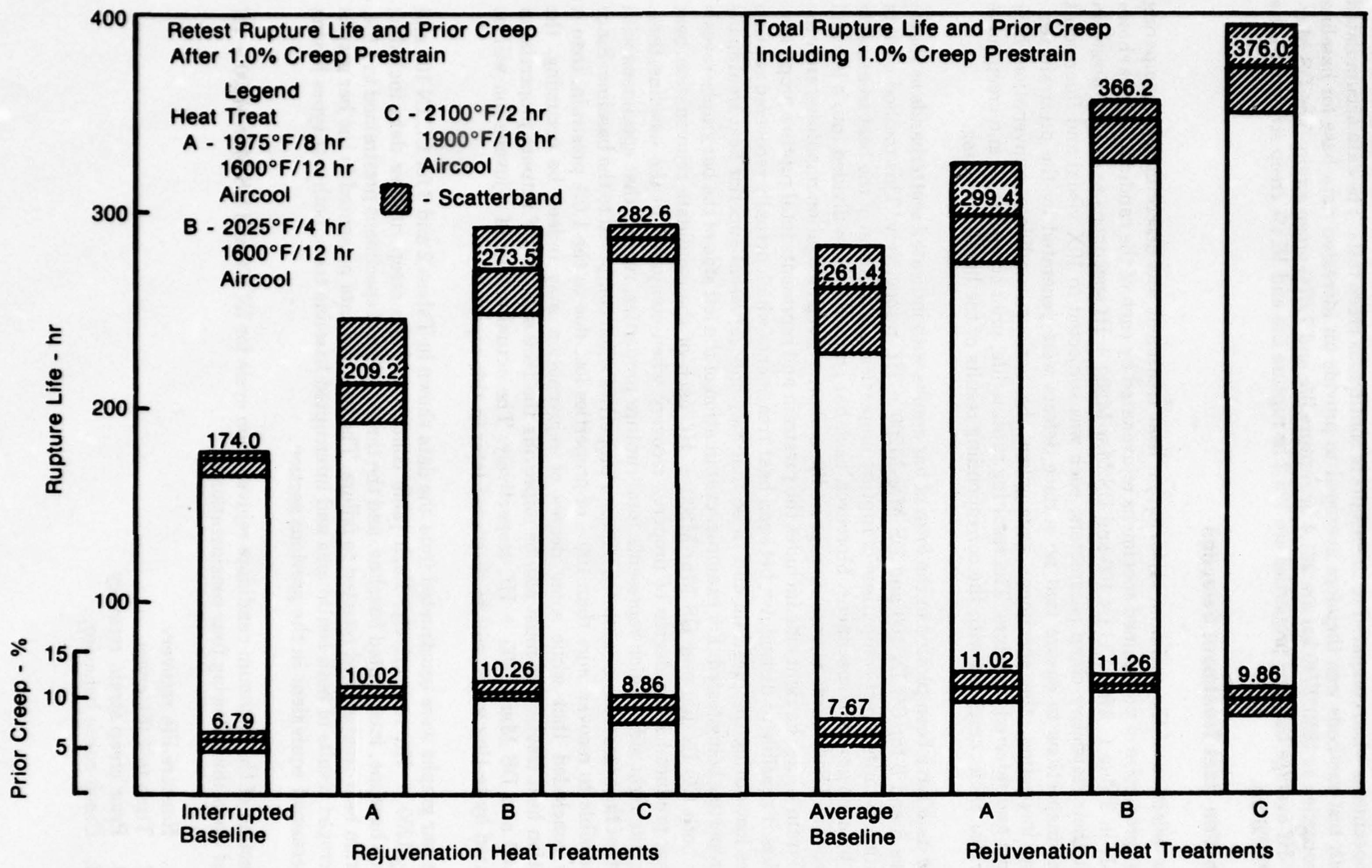

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Figure 5. CC IN 100 Creep Properties Comparison for Specimens With and Without Candidate Rejuvenation Heat Treatments, 1650°F/40 ksi

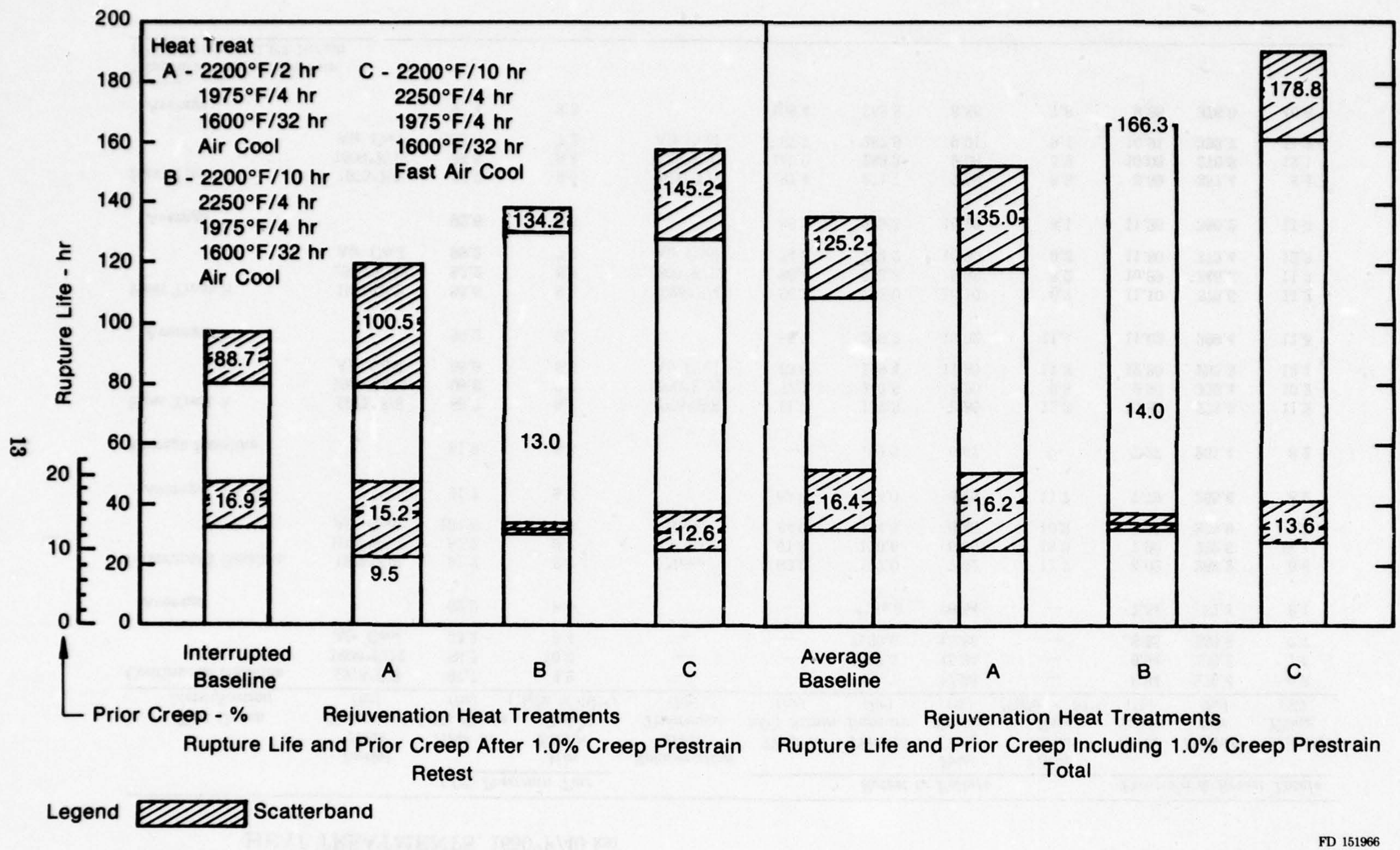

Figure 6. DS MAR-M200 + Hf Creep Properties Comparison for Specimens With and Without Candidate Rejuvenation Heat Treatments, 1800°F/28 ksi

TABLE 2. CC IN 100 CREEP TEST DATA FOR SPECIMENS WITH AND WITHOUT CANDIDATE REJUVENATION HEAT TREATMENTS, 1650°F/40 ksi

		1.0% Prestrain Test			Retest to Failure				Prestrain & Retest Totals		
Test Group Identification	*Initial Heat Treatment (hr)*	*Time to 1.0% Strain (hr)*	*Min Strain Rate (%/hr × 10^{-3})*	*Rejuvenation Heat Treatment (hr)*	*Time to 1.0% Strain (hr)*	*Time to Rupture (hr)*	*Prior Creep Strain (%)*	*Min Strain Rate (%/hr × 10^{-3})*	*Creep Strain (%)*	*Rupture Life (hr)*	*Rupture Elong. (%)*
Continuous Baseline	1975°F/8	97.7	8.2	—	—	*181.7	†7.84	—	8.84	279.4	9.3
	1600°F/12	85.7	10.0	—	—	*152.5	†5.94	—	6.94	238.2	7.5
	Air Cool	93.2	8.4	—	—	*160.6	†5.85	—	6.85	253.8	7.7
Average		92.2	8.9		—	*164.9	†6.54	—	7.54	257.1	8.1
Interrupted Baseline	1975°F/8	91.2	8.8	None	62.0	177.0	7.02	11.7	8.02	268.2	8.6
	1600°F/12	82.2	9.7	None	61.8	170.6	6.90	13.0	7.90	252.8	⅛.4
	Air Cool	101.6	7.6	None	64.0	174.3	6.45	10.3	7.45	275.9	7.7
Average		91.7	8.7		62.6	174.0	6.79	11.7	7.79	265.6	8.2
Average Baseline		91.9	8.8		—	169.5	6.67	—	7.67	261.4	8.2
Heat Treat A	1975°F/8	86.2	9.7	1975°F/8	61.3	187.3	9.85	12.3	10.85	273.5	11.2
	1600°F/12	98.6	7.7	1600°F/12	72.1	240.8	8.90	9.8	9.90	339.4	10.2
	Air Cool	85.9	9.5	Air Cool	63.6	199.4	11.30	11.3	12.30	285.3	13.1
Average		90.2	9.0		65.7	209.2	10.02	11.1	11.02	299.4	11.5
Heat Treat B	1975°F/8	85.6	9.5	2025°F/4	96.2	293.0	10.10	6.7	11.10	378.6	11.2
	1600°F/12	93.2	8.3	1600°F/12	88.4	253.3	9.89	8.2	10.89	346.5	11.3
	Air Cool	99.2	7.7	Air Cool	74.3	274.2	10.80	9.3	11.80	373.4	12.3
Average		92.6	8.5		86.3	273.5	10.26	8.1	11.26	366.2	11.6
Heat Treat C	1975°F/8	85.7	9.5	2100°F/2	97.4	271.7	7.59	8.3	8.59	357.4	8.4
	1600°F/12	88.5	8.8	1700°F/16	140.0	288.3	9.08	5.8	10.08	376.8	12.1
	Air Cool	105.9	7.2	Air Cool	87.7	287.8	9.91	9.4	10.91	393.7	11.3
Average		93.4	8.5		108.4	282.6	8.86	7.8	9.86	376.0	10.6

*Rupture Life — 1.0% Life
†Prior Creep — 1.0% Strain

TABLE 3. DS MAR-M200 × Hf CREEP TEST DATA FOR SPECIMENS WITH AND WITHOUT CANDIDATE REJUVENATION HEAT TREATMENTS, 1800°F/28 ksi

		1.0% Prestrain Test			Retest to Failure				Prestrain & Retest Totals		
Test Group Identification	Initial Heat Treatment (hr)	Time to 1.0% Strain (hr)	Min Strain Rate (%/hr × 10^{-3})	Rejuvenation Heat Treatment (hr)	Time to 1.0% Strain (hr)	Time to Rupture (hr)	Prior Creep Strain (%)	Min Strain Rate (%/hr × 10^{-3})	Creep Strain (%)	Rupture Life (hr)	Rupture Elong. (%)
Continuous Baseline	2200°F	41.2	2.22	—	—	*78.6	†13.2	—	14.2	119.8	19.5
	1975°F/4	43.3	2.08	—	—	*84.2	†12.6	—	13.6	127.5	16.4
	1600°F/32	42.5	1.89	—	—	*89.4	†11.9	—	12.9	131.9	15.0
	Air Cool	39.4	2.30	—	—	*86.7	†19.7	—	20.7	126.1	23.4
Average		41.6	2.12		—	*84.7	†14.4	—	15.4	126.3	18.6
Interrupted Baseline	2200°F/2	40.1	2.40	None	30.5	96.8	13.4	2.86	14.4	136.9	16.3
	1975°F/4	38.5	2.36	None	27.9	89.6	17.7	3.20	18.7	128.2	24.3
	1600°F/32	26.1	3.30	None	23.5	79.6	19.6	4.00	20.6	106.4	23.7
	Air Cool										
Average		34.9	2.36		27.3	88.7	16.9	3.35	17.9	123.8	21.4
Average Baseline		38.7	2.41		—	86.5	15.4	—	16.4	125.2	19.8
Heat Treat A	2200°F/2	32.2	2.67	2200°F/2	32.3	119.8	19.6	2.87	20.6	152.2	29.6
	1975°F/4	31.0	2.94	1975°F/4	29.7	103.0	16.6	3.22	17.6	134.2	18.8
	1600°F/32	38.2	2.24	1600°F/32	26.9	78.6	9.5	2.93	10.5	118.7	12.9
	Air Cool			Air Cool							
Average		33.8	2.62		29.6	100.5	15.2	3.01	16.2	135.0	20.4
Heat Treat B	2200°F/2	29.1	3.06	2200°F/10	44.9	135.9	13.5	2.13	14.5	166.4	18.9
	1975°F/4	33.5	2.76	2250°F/4	40.0	132.4	12.4	2.27	13.4	166.1	14.4
	1600°F/32	28.3	2.94	1975°F/4		**No Test		**No Test			
	Air Cool			1600°F/32							
				Air Cool							
Average		30.3	2.92		42.5	134.2	13.0	2.20	14.0	166.3	16.7
Heat Treat C	2200°F/2	31.5	2.83	2200°F/10	47.1	127.0	12.2	1.94	13.2	161.5	13.9
	1975°F/4	32.4	2.50	2250°F/4	49.8	151.6	15.2	1.85	16.2	184.9	19.5
	1600°F/32	30.7	2.82	1975°F/4	52.5	157.1	10.5	1.72	11.5	189.9	13.6
	Air Cool			1600°F/32							
				Fast Air Cool							
Average		31.5	2.72		49.8	145.2	12.6	1.84	13.6	178.8	15.7

**Incorrect test parameters used in retest
*Rupture Life — 1.0% Life
†Prior Creep — 1.0% Strain

Based upon the information shown in the left and right side of the bar graph in Figure 5, the most favorable rejuvenation heat treatment in terms of rupture life and prior creep strain for CC IN 100 was heat treatment B, the 2025°F/4 hr + 1600°F/12 hr - AC (air cool) coat and age cycle. Compared to retest results obtained after the 1.0% prestrain (left side of graph) average rupture life and prior creep strain improved from 169.5 to 273.5 hr and 6.67 to 10.26% for the interrupted baseline versus rejuvenated specimens. Comparison of these improved retest properties with the average baseline results of 261.4 hr and 7.67% (right side of graph) indicates that the 1.0% prestrain life is recovered with little to no improvement while the 1.0% prestrain elongation is recovered with an additional increase in prior creep at failure. According to the right side of the bar graph, which includes the sum of the prestrain and the recovered plus improved retest properties, average rupture life and total creep strain of specimens prestrained to 1.0% and retested to failure increased from 261.4 to 366.2 hr and 7.67 to 11.26% with rejuvenation heat treatment "B." Specimens with the 2100°F/2 hr - AC + 1700°F/16 hr - AC heat treatment exhibited the highest rupture life improvement with 282.6 hr retest and 376.0 total hours; however, the lower temperature rejuvenation treatment produced significantly higher prior creep strain improvement and also represented a coating cycle temperature more readily adaptable to the current production coating process. These factors were considered more important than the slight advantage in rupture life gained by the higher temperature heat treatment.

As shown in the bar graph of Figure 6, the heat treatment which restored the most favorable combination of rupture life and prior creep strain for DS Mar-M200 + Hf was heat treatment "C," the 2200°F/10 hr + 2250°F/4 hr fast air cool duplex cycle. Retest results after 1.0% prestrain (left side of bar graph) indicate that average rupture life improved for the baseline versus the rejuvenated specimens from 86.4 to 145.2 hr while prior creep strain declined from 15.4 to 12.6%. These rejuvenated retest properties, when compared to the average baseline of 125.2 hr and 16.4% indicate that the 1.0% prestrain life is recovered and substantially improved while the prior creep at failure is reduced. The total rupture lives of specimens prestrained to 1.0% and retested to failure increased from the baseline average of 125.2 to 178.8 hr with rejuvenation heat treatment "C," while total creep strain decreased from 16.4 to 13.6%. The decrease in creep strain for specimens with the selected rejuvenation heat treatment was not considered serious in view of the high creep ductility inherent in DS Mar-M200 + Hf.

Another important factor in the selection of the most effective of the candidate rejuvenation heat treatments was the time required to reach 1.0% creep, sometimes called the creep strength. This is an especially important consideration when applied to turbine airfoils since blade growth is one major contributor to current scrappage rates.

The time to 1.0% creep has been plotted in Figures 7 and 8 for CC IN 100 and DS Mar-M200 + Hf, respectively. It is evident from these figures that each of the candidate heat treatments was capable of recovering at least a portion of the creep strength which was lost as a result of the initial 1.0% creep strain.

As shown in Figure 7, CC IN 100 exhibited the maximum amount of recovery when heat treated at 2100°F/2 hr + 1700°F/10 hr. However, the lower temperature heat treatment, 2025°F/4 hr + 1600°F/12 hr, was also capable of significant property recovery and, based upon the previously discussed economics of utilizing a rejuvenation cycle which can also double as a coating diffusion cycle (2100°F is too hot), the 2025°F heat treatment was considered to be the best all-around choice.

Figure 8 reveals that DS Mar-M200 + Hf responded most favorably to the 2200°F/10 hr + 2250°F/4 hr + 1975°F/4 + 1600°F/32 hr FAC duplex cycle. This observation is in agreement with the conclusions previously reached based upon the analysis of rupture life and prior creep strain.

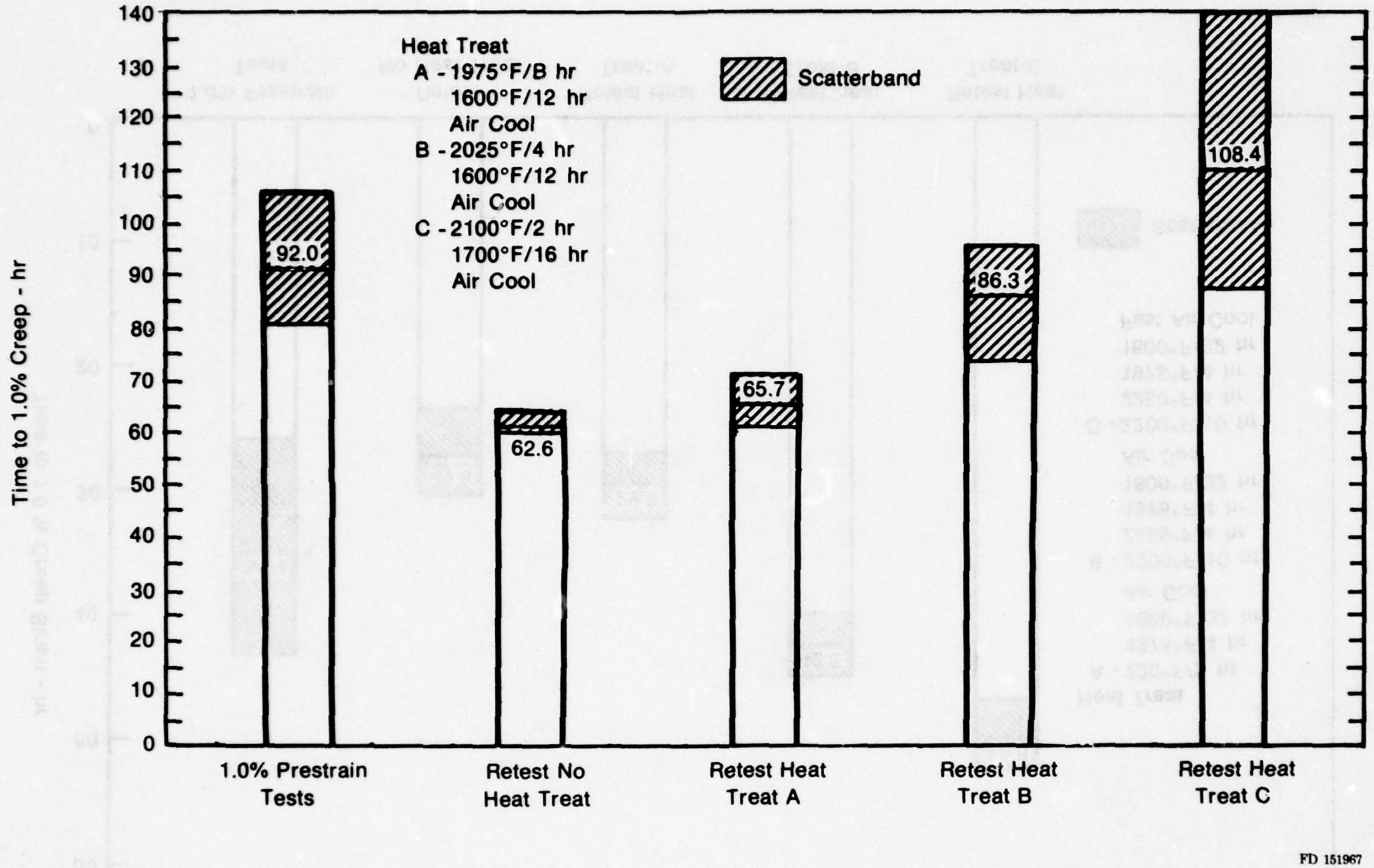

Figure 7. CC IN 100 Prestrain and Retest Comparison for Time to 1.0% Strain, 1650°F/40 ksi

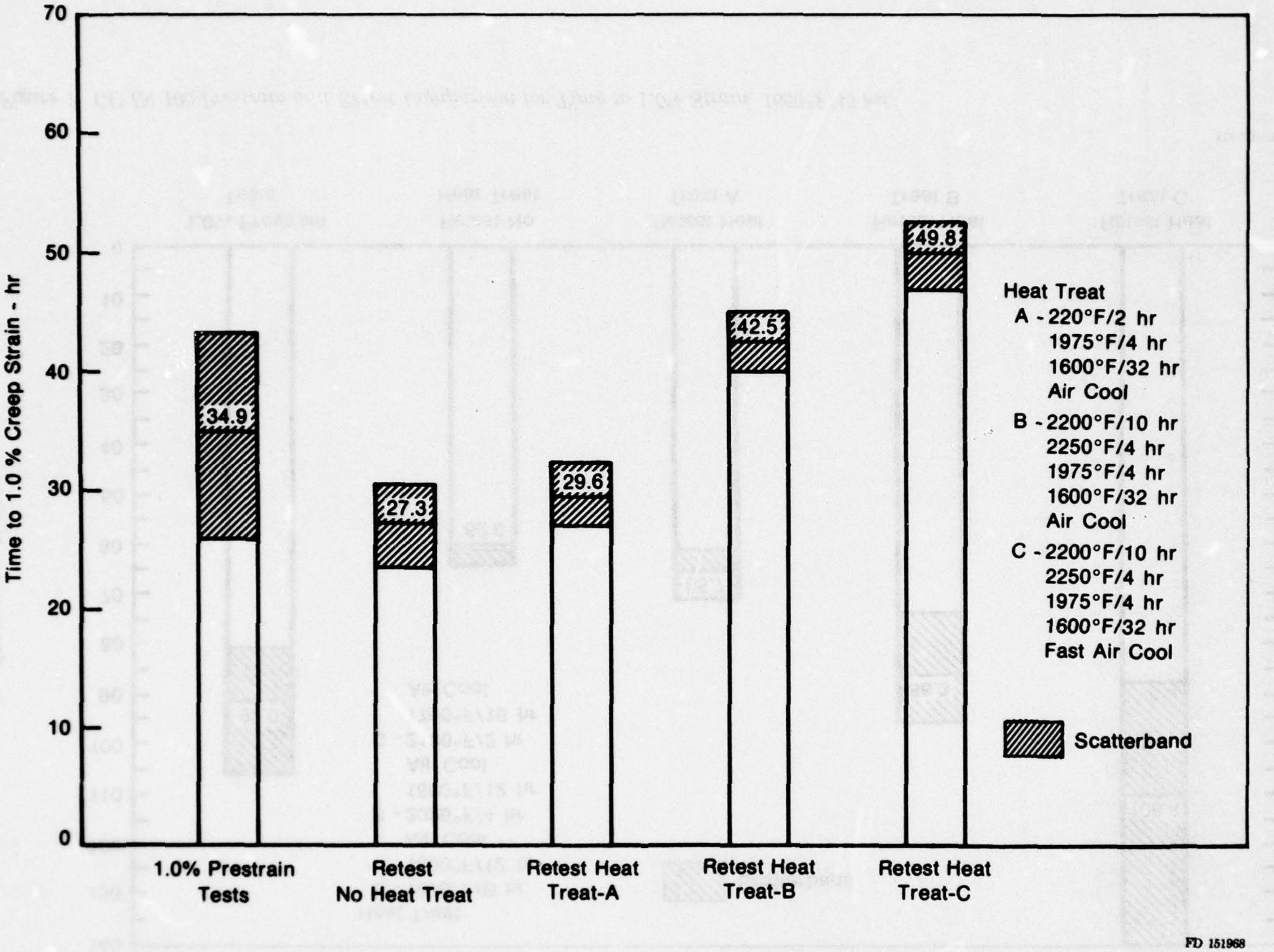

Figure 8. DS MAR-M200 + Hf Prestrain and Retest Comparison for Time to 1.0% Strain, 1800°F/28 ksi

Creep strength recovery can be further analyzed by plotting the creep data and comparing the minimum creep rate before and after rejuvenation heat treatments. Data plots can also be utilized to confirm the recurrence of the 1st-stage creep mode after rejuvenation.

The minimum creep rate data before and after retest has been plotted as shown in Figure 9 for CC IN 100 and Figure 10 for DS Mar-M200 + Hf to illustrate the effects of the rejuvenation cycles on the reinitiated 2nd-stage creep that was observed in all retested specimens. The graphs for both alloys show a significant increase in the minimum creep rates for specimens that were retested either without a rejuvenation heat treatment or with the standard solution, coat and age cycles (heat treat "A") for each alloy. The higher temperature rejuvenation cycles, B and C, for each alloy, however, produce definite recovery of and a possible decrease in the minimum creep rate of retested specimens as compared to that observed before rejuvenation.

Representative creep curves illustrating these observations have been plotted for CC IN 100 and DS Mar-M200 + Hf in Figures 11 through 16. In Figures 11 and 12, 1.0% prestrain curves have been plotted along with the first 1.0% of the interrupted baseline retest curves. Evaluation of the plotted creep curves indicated that even for specimens prestrained to 1.0% and retested to failure without a rejuvenation heat treatment (baseline) some degree of 1st- and 2nd-stage creep was in all cases reinitiated. However, the retest specimens did not receive a rejuvenation heat treatment and it is evident from the curves that the creep rate for each alloy is higher than during the initial 1.0% prestrain. A similar 1.0% prestrain curve has been plotted for CC IN 100 and DS Mar-M200 + Hf in Figures 13 and 14 along with the first 1.0% of the retest curve; however, in this case the CC IN 100 retest specimens received the candidate heat treatment B, and the DS Mar-M200 + Hf retest specimens received the candidate heat treatment C. Examination of the curves reveals that the minimum creep rate has been substantially reduced during the rejuvenated retest compared to the prestrain test. It should be pointed out that the 1.0% prestrain and rejuvenated retest curves of Figure 13 illustrate one of the most dramatic cases of creep rate improvement for CC IN 100 while the curves of Figure 14 are more representative of the creep rate reduction observed for rejuvenated DS Mar-M200 + Hf. The effect of the selected rejuvenation heat treatments on minimum creep rates will be examined in more detail with a more definitive population of test specimens as part of the evaluation of multiple creep rejuvenation.

The reinitiation of 1st- and 2nd-stage creep modes, and the recovery of the initial minimum creep rate confirmed the selection of heat treatments found most favorable on the basis of rupture life and creep strain improvement. These heat treatments were the 2025°F/4 hr + 1600°F/12 hr - AC coat and age cycle (heat treat B) for CC IN 100 and the 2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr - FAC duplex solution, coat, and age cycle (heat treat C) for DS Mar-M200 + Hf. A representative comparison of the creep curves for an interrupted baseline retest, a continuous baseline test and a retest with the selected rejuvenation heat treatment is illustrated in Figures 15 and 16 for CC IN 100 and DS Mar-M200 + Hf, respectively.

The 2025°F/4 hr + 1600°F/12 hr cycle for CC IN 100 and the 2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr cycle for DS Mar-M200 + Hf were the only rejuvenation heat treatments used in the remaining test evaluations. Therefore, the terms "rejuvenation heat treat," "rejuvenation cycle," and "rejuvenated," used in the remainder of this report will refer to one or both of these selected heat treatments unless specifically stated otherwise.

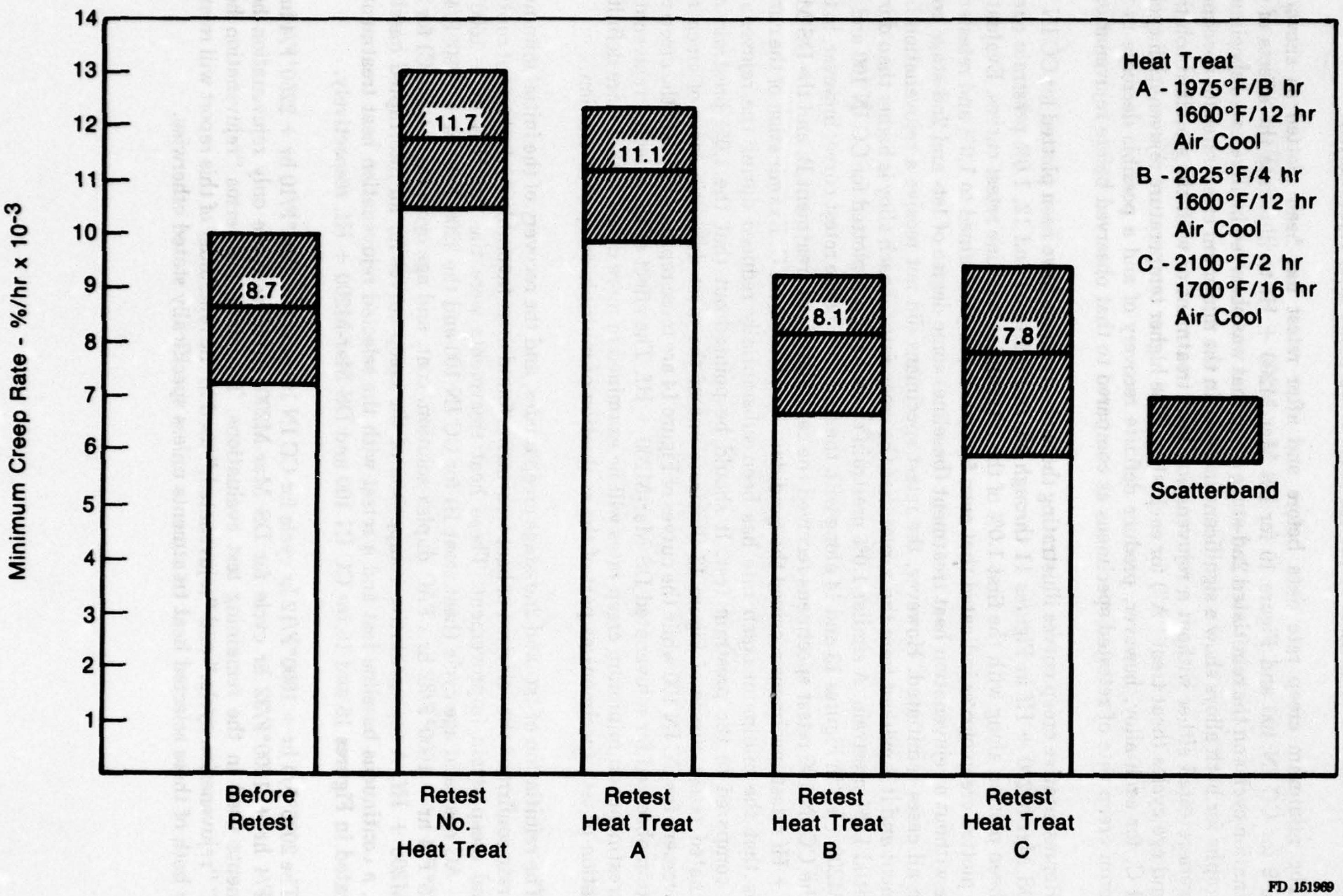

Figure 9. Effect of Rejuvenation Heat Treatments on the Minimum Creep Rate of CC IN 100 at 1650°F/40 ksi

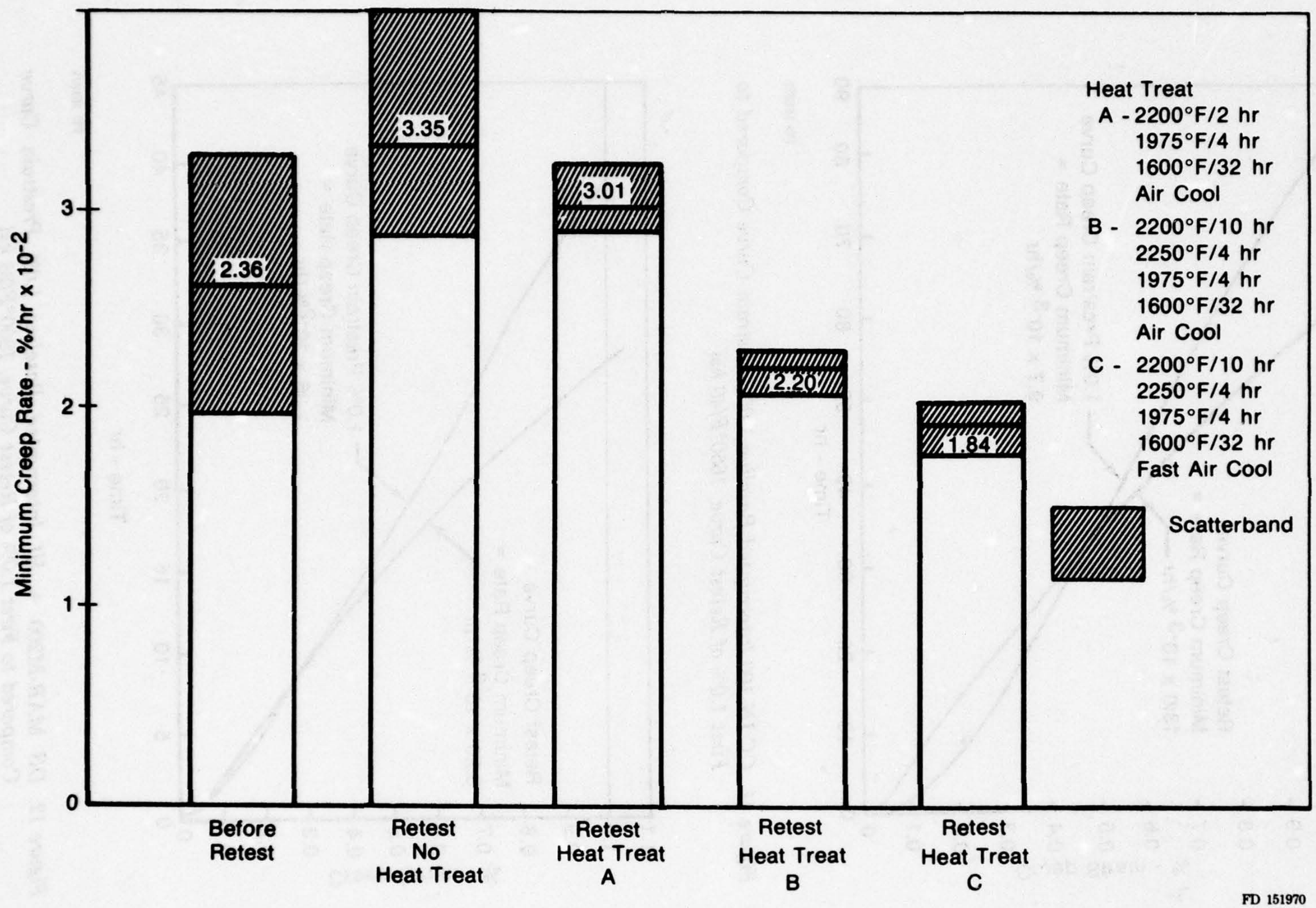

Figure 10. Effect of Rejuvenation Heat Treatments on the Minimum Creep Rate of DS MAR-M200 + Hf at 1800°F/28 ksi

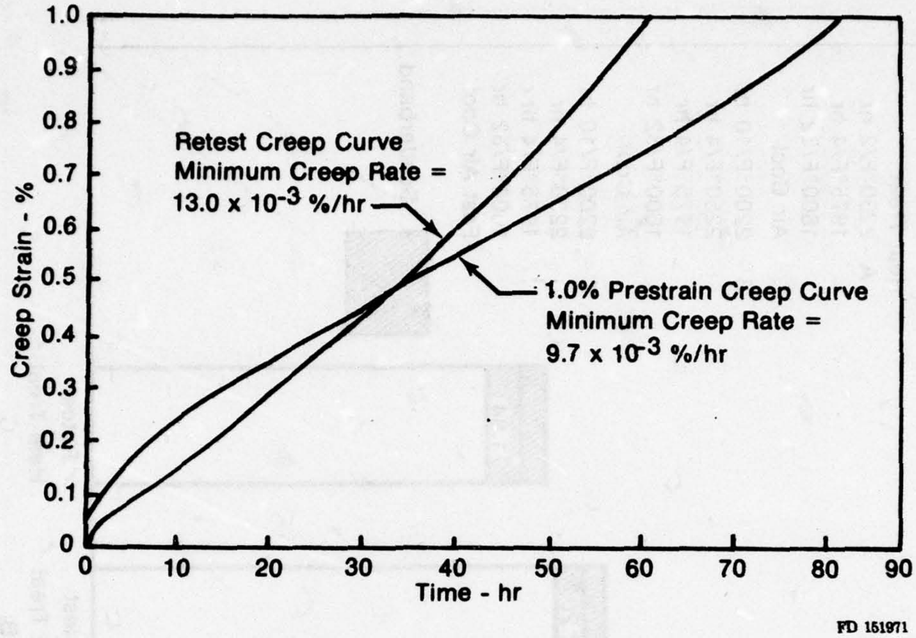

Figure 11. CC IN 100 Interrupted Baseline 1.0% Prestrain Curve Compared to First 1.0% of Retest Curve, 1650°F/40 ksi

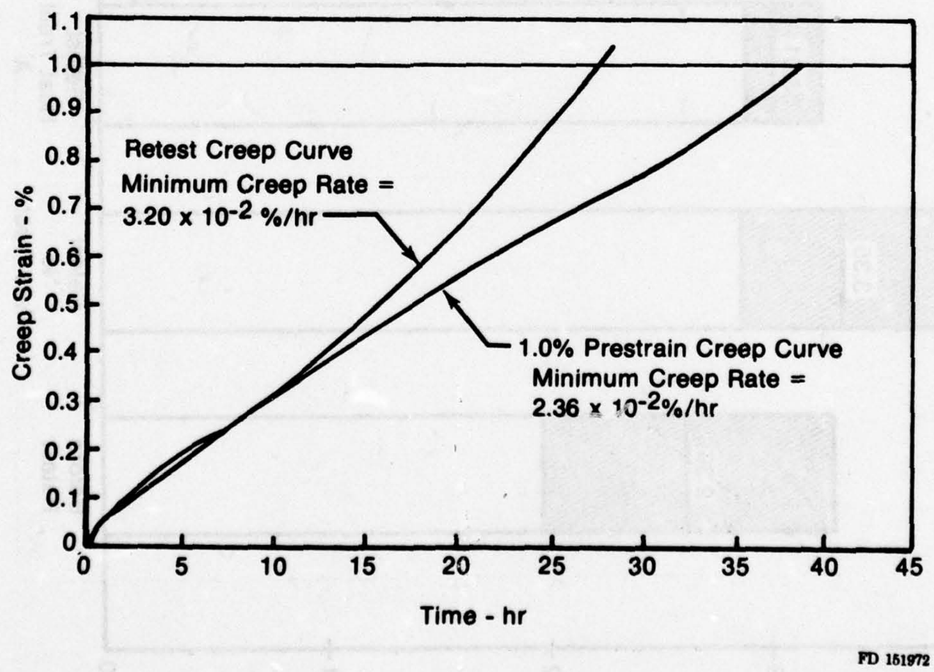

Figure 12. DS MAR-M200 + Hf Interrupted Baseline 1.0% Prestrain Curve Compared to First 1.0% of Retest Curve, 1800°F/28 ksi

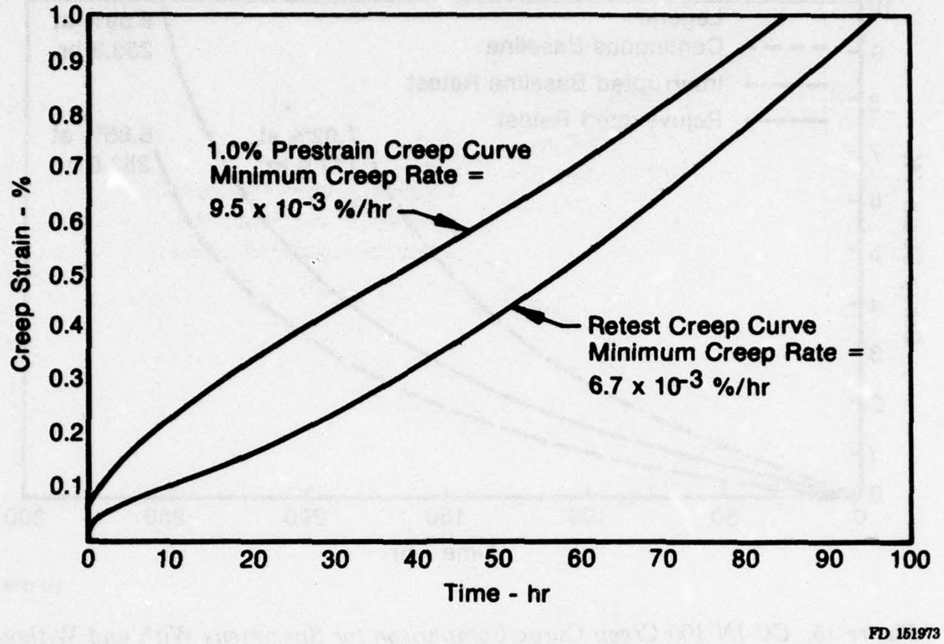

Figure 13. CC IN 100 1.0% Prestrain Curve Compared to First 1.0% of Retest Curve After Application of Rejuvenation Heat Treatment B, 1650°F/40 ksi

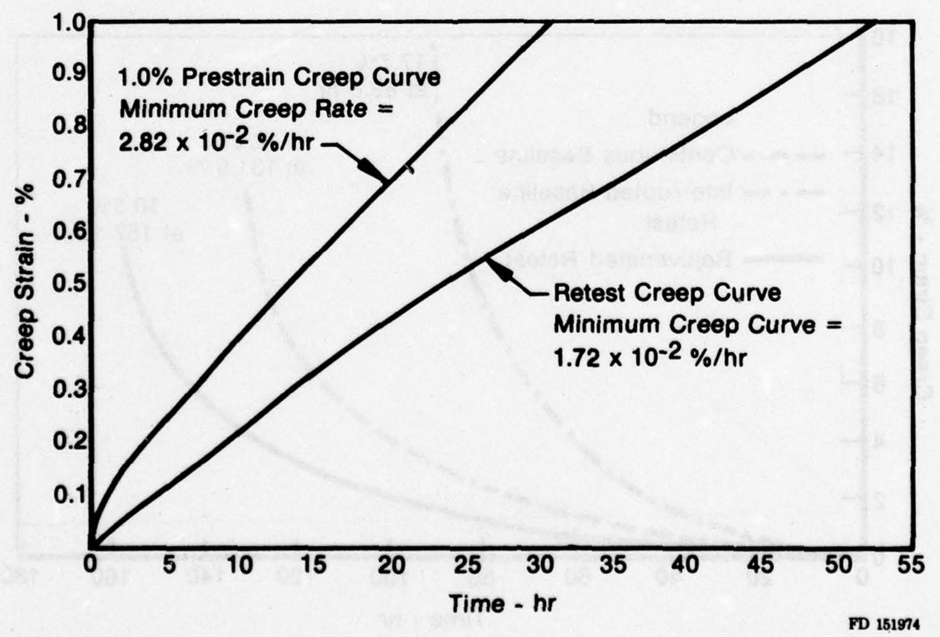

Figure 14. DS MAR-M200 + Hf 1.0% Prestrain Curve Compared to First 1.0% of Retest Curve After Application of Rejuvenation Heat Treatment C, 1800°F/28 ksi

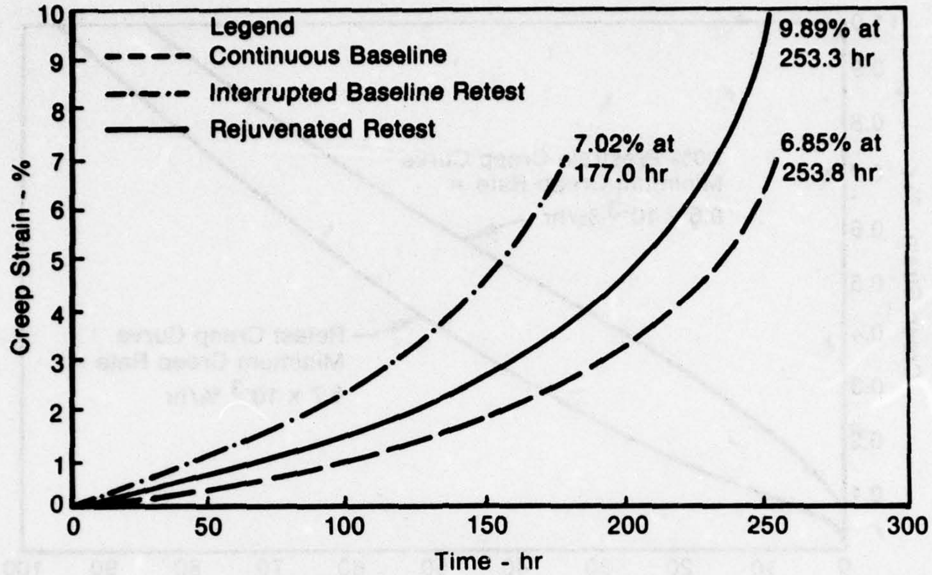

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Figure 15. CC IN 100 Creep Curve Comparison for Specimens With and Without Rejuvenation Heat Treatment

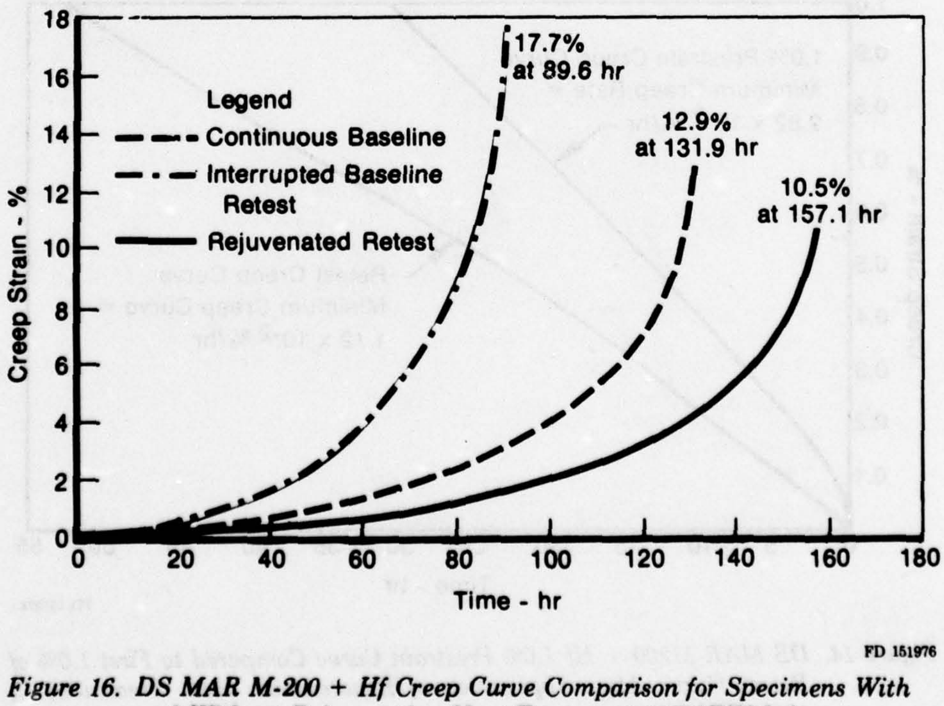

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Figure 16. DS MAR M-200 + Hf Creep Curve Comparison for Specimens With and Without Rejuvenation Heat Treatment 1800°F/28 ksi

Effect of Rejuvenation Heat Treatment on Mechanical Property Requirements

As discussed in Appendix A, as-received CC IN 100 and DS Mar-M200+ Hf specimens were initially heat treated (standard heat treatment) and tested to the requirements of the applicable Pratt & Whitney material specification. This work was designed to confirm that these specimens met minimum property requirements in 1400°F creep and 1800°F stress rupture and to establish baseline properties against which subsequent tests could be compared. The establishment of the thermal rejuvenation process again necessitated confirmation that specimens, both with and without the 1.0% creep prestrain, heat treated to these parameters were capable of meeting minimum specification properties and to compare these properties with the baseline obtained with standard heat treated specimens. The three test conditions are illustrated by the flow chart in Figure 17 and the resulting data are presented in Table 4 for CC IN 100 and Table 5 or DS Mar-M200 + Hf. Bar graph comparisons of the data for each of the three conditions are presented in Figures 18 through 23.

The CC IN 100 specimens given the rejuvenation heat treatments without the 1.0% prestrain met and exceeded the room temperature tensile and 1800°F/24 ksi stress rupture requirements and the data were similar to the results obtained with specimens from the standard heat treatment alone.

The specimens prestrained to 1.0% followed by rejuvenation heat treatment also exceeded tensile and stress rupture requirements but with lower properties than those of the standard heat treated specimens. This seems to indicate that property recovery was not complete. These observations are illustrated for tensile in Figure 18 and for stress-rupture in Figure 19.

The results of the 1400°F/85 ksi creep-rupture tests, which evaluate the minimum ductility range of CC IN 100, are illustrated in Figure 20. It can be seen that the rejuvenation heat treated specimen without the 1.0% prestrain exceeds specification requirements, but with a significant reduction in rupture life and creep strain as compared to the specimen with the standard heat treatment. The specimen with the 1.0% prestrain and rejuvenation heat treatment exhibits a further reduction in rupture life and a prior creep strain that has degraded to 1.81% which is below the PWA 658 minimum requirement of 2.0%. These results indicate that while the rejuvenation heat treatment can be expected to maintain the 1800°F stress rupture properties, a slight debit will be incurred with 1400°F creep rupture.

Comparison of the DS Mar-M 200 + Hf results for room temperature tensile, 1400°F/100 ksi creep, and 1800°F/32 ksi creep/stress-rupture are shown in Figures 21, 22, and 23, respectively. For the tensile test, while the specimen with the standard plus rejuvenation heat treatments failed to meet the 0.2% yield and ultimate strength minimums, the data were similar to the specimens with the standard heat treatment alone. The tensile elongation, however, fell below the 5.0% minimum to 4.7% as compared to 6.0% for the standard heat treatment. Surprisingly, the specimen that received the rejuvenation cycle after 1.0% prestrain at 1800°F/28 ksi exceeded all tensile requirements although the elongation was still low in the ductility range at 5.3%.

Rejuvenation heat treated specimens, with and without the 1.0% prestrain, readily passed the 1400°F/100 ksi creep requirements with 48 hr creep strains not exceeding 4.0%. These strains remained within close range of the standard heat treated specimen.

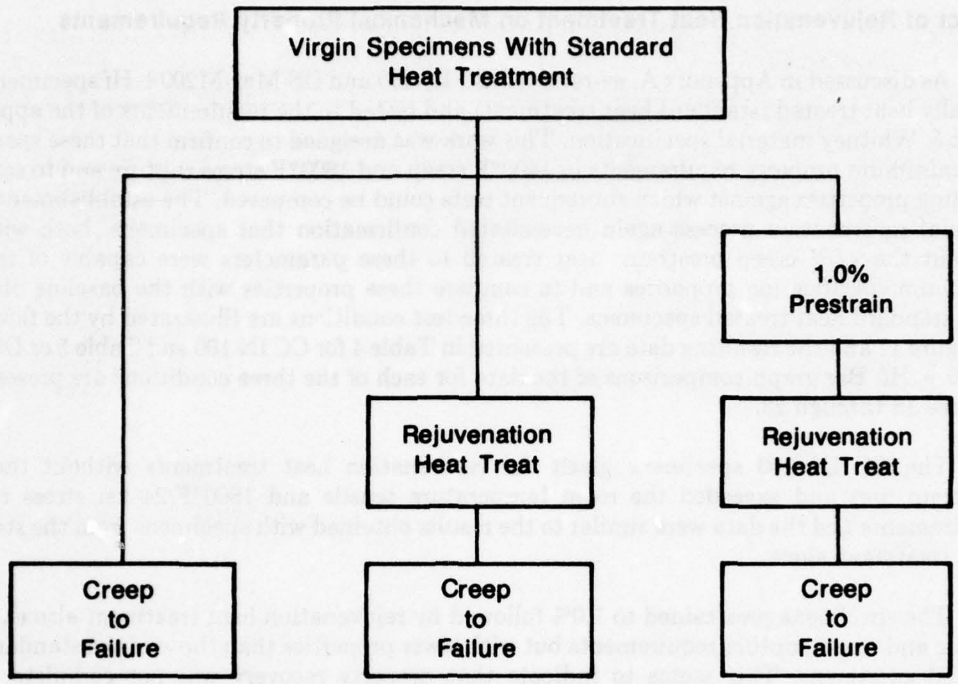

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Figure 17. Effect of Rejuvenation Heat Treatment on Mechanical Properties

TABLE 4. EFFECT OF *REJUVENATION HEAT TREATMENT ON PWA 658 MECHANICAL PROPERTY REQUIREMENTS

Specimen Condition	*Test Type*	*0.2% Yield Strength (ksi)*	*Tensile Strength (ksi)*	*Rupture Life (hr)*	*Creep/ Elongation (%)*
Std. H.T. Baseline	RT Ten	118.1	141.2		12.0
Std. H.T. and Rejuv. H.T.	RT Ten	111.2	158.6		7.0
1.0% Prestrain and Rejuv. H.T.	RT Ten	110.5	133.3		8.0
PWA 658 Spec	RT Ten	105	115		5
Std. H.T. Baseline	1800°F/29 ksi			44.5	9.9
Std. H.T. and Rejuv. H.T.	1800°F/29 ksi			46.5	11.7
1.0% Prestrain and Rejuv. H.T.	1800°F/29 ks			28.6	9.5
PWA 658 Spec	1800°F/29 ksi			23	4
Std. H.T. Baseline	1400°F/85 ksi			764.2	**4.49
Std. H.T. and Rejuv. H.T.	1400°F/85 ksi			493.4	**2.54
1.0% Prestrain and Rejuv.H.T.	1400°F/85 ksi			333.7	**1.81
PWA 658 Spec	1400°F/85 ksi			23	**2

*2025°F/4 hr — 1600°F/12 hr-air cool
**Prior Creep

TABLE 5. EFFECT OF *REJUVENATION HEAT TREATMENT ON PWA 1422 MECHANICAL PROPERTY REQUIREMENTS

Specimen Condition	*Test Type*	*0.2% Yield Strength (ksi)*	*Tensile Strength (ksi)*	*Rupture Life (hr)*	*Elongation (%)*	*20 Hour Creep (%)*
Std. H.T. Baseline		123.5	140.2		6.0	
Std. H.T. + Rejuv. H.T.	RT Ten	115.0	141.5		4.7	
1.0% Prestrain + Rejuv. H.T.		143.7	158.7		5.3	
PWA 1422 Mat'l Man. Min	RT Ten	130	150		5	
Std. H.T. Baseline				**48	2.34	
Std. H.T. + Rejuv. H.T.	1400°F/100 ksi Creep			**48	2.18	
1.0% Prestrain + Rejuv. H.T.				**48	2.49	
PWA 422 Spec	1400°F/100 ksi Creep			**48	4 max	
Std. H.T. Baseline				42.5	20.5	1.8
Std. H.T. + Rejuv. H.T.	1800°F/32 ksi			24.6	18.3	7.5
Std. H.T. + Rejuv. H.T.	Creep/Stress-Rupture			31.6	5.6	1.7
1.0% Prestrain + Rejuv. H.T.				64.0	12.1	1.1
PWA 1422 Spec	1800°F/32 ksi Creep/Stress Rupture			32	10	2.0 max

*2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr-fast air cool
**Test discontinued at 48 hr.

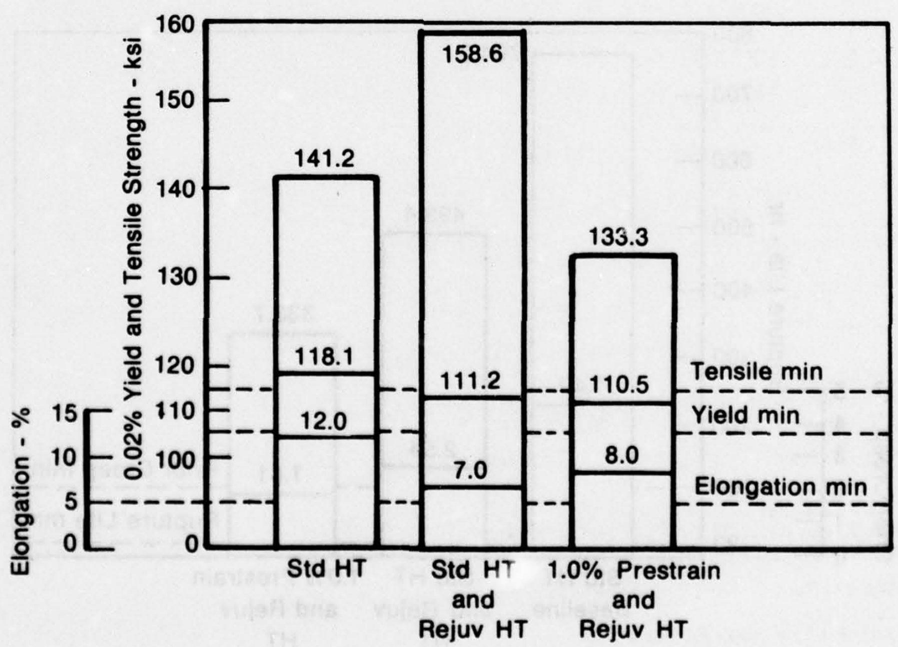

Figure 18. Effect of Rejuvenation Heat Treatment on CC IN 100 Room Temperature Tensile Properties

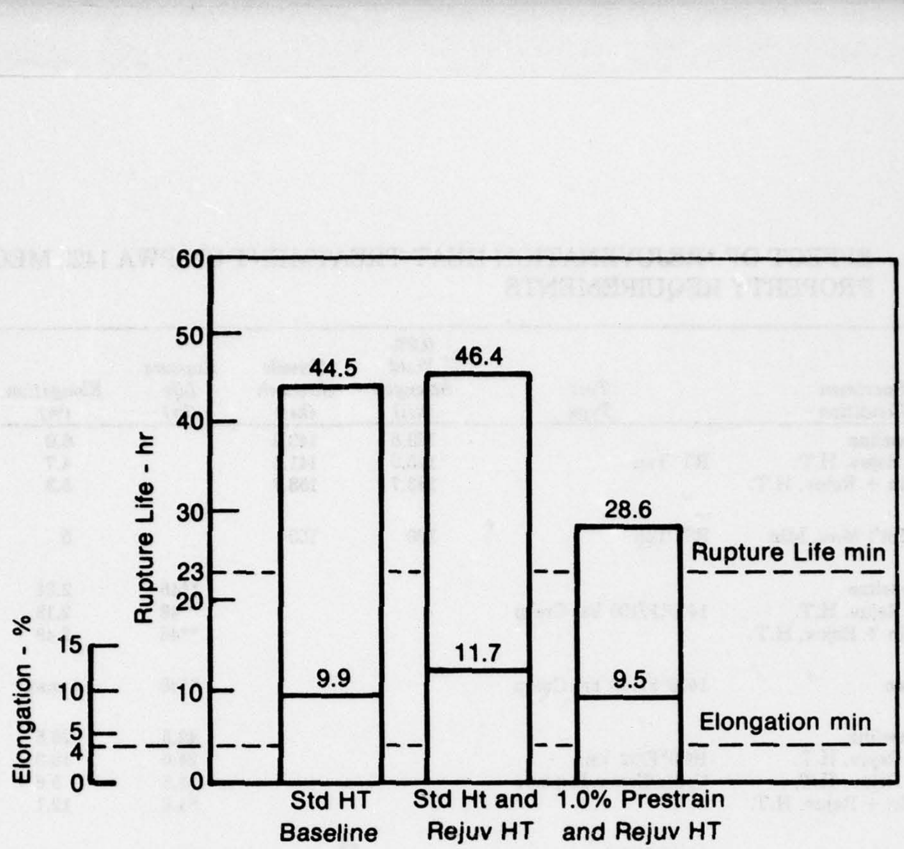

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Figure 19. Effect of Rejuvenation Heat Treatment on 1800°F/29 ksi Stress Rupture Properties of CC IN 100

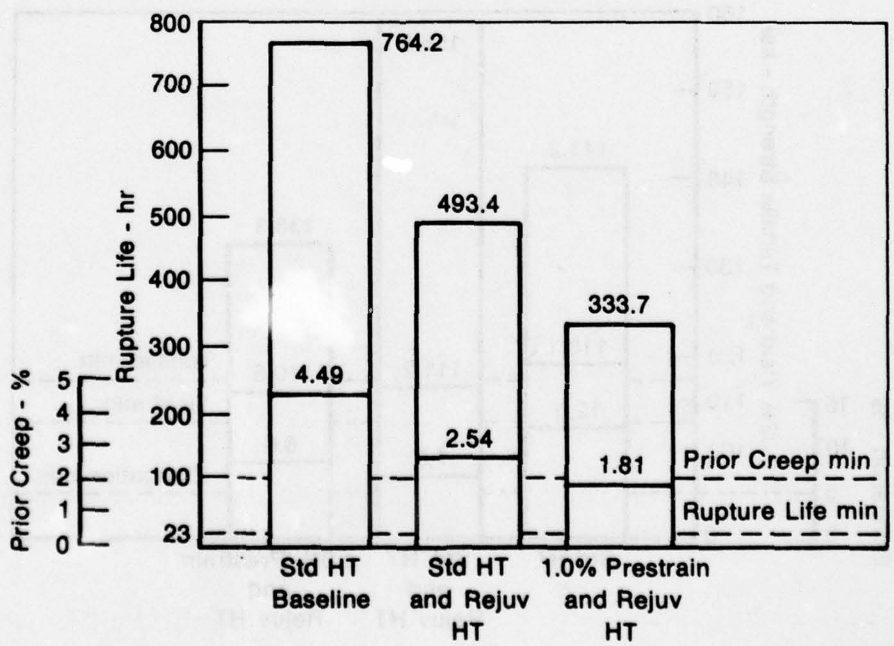

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Figure 20. Effect of Rejuvenation Heat Treatment on 1400°F/85 ksi Creep Rupture Properties of CC IN 100

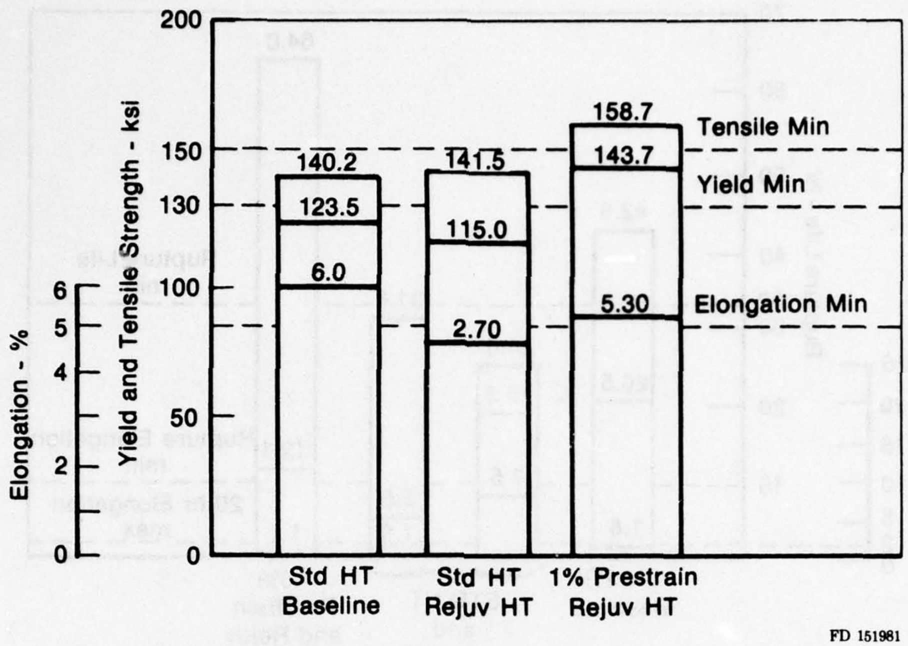

Figure 21. Effect of Rejuvenation Heat Treatment on DS MAR-M200 + Hf Room Temperature Tensile Properties

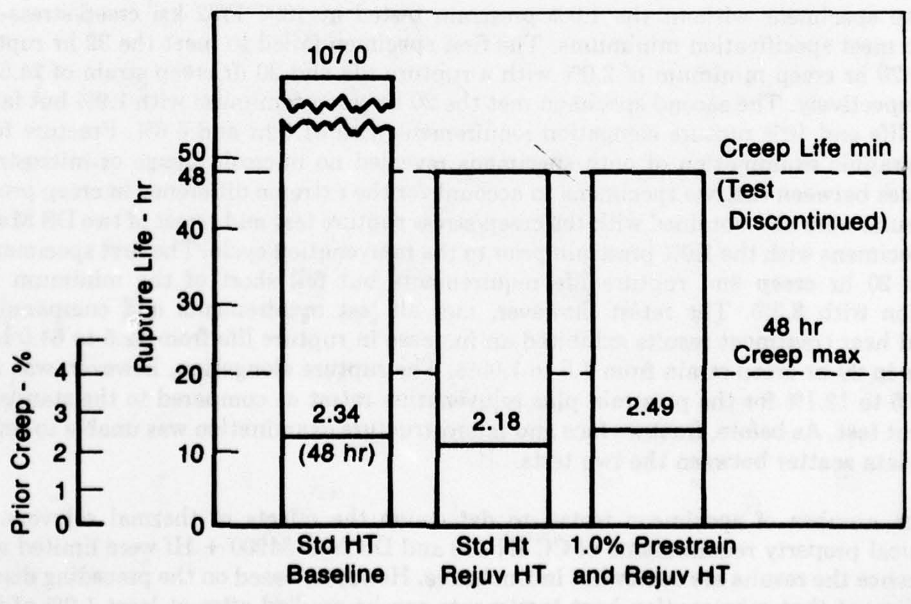

Figure 22. Effect of Rejuvenation Heat Treatment on 1400°F/100 ksi Creep Properties of DS MAR-M200 + Hf

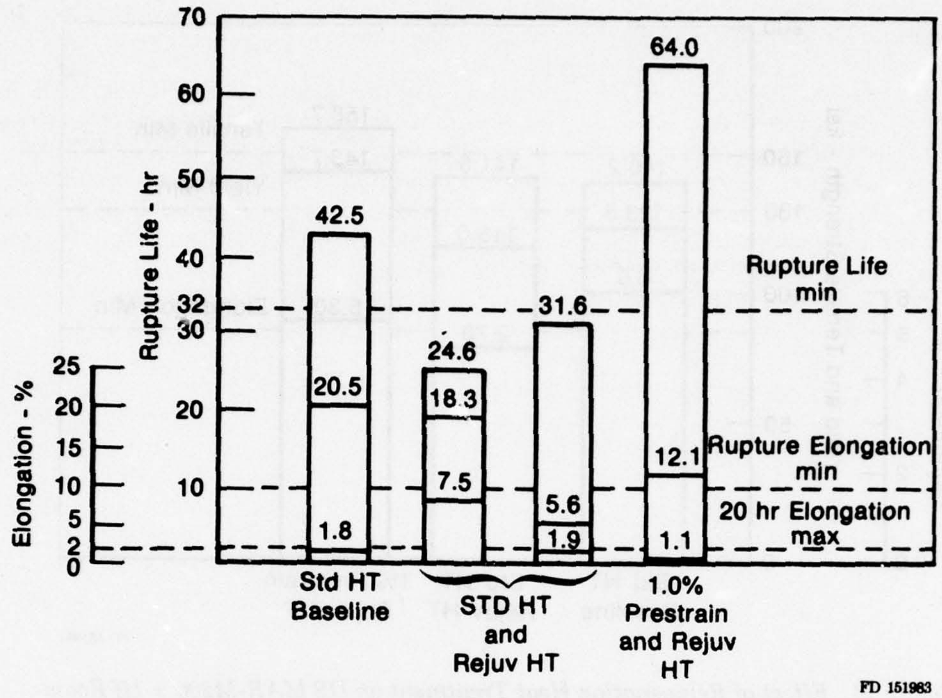

Figure 23. Effect of Rejuvenation Heat Treatment on 1800°F/32 ksi Creep/Stress — Rupture Properties of DS MAR-M200 + Hf

Two specimens without the 1.0% prestrain tested at 1800°F/32 ksi creep/stress-rupture failed to meet specification minimums. The first specimen failed to meet the 32 hr rupture life and the 20 hr creep minimum of 2.0% with a rupture life and 20 hr creep strain of 24.6 hr and 7.5%, respectively. The second specimen met the 20 hr creep minimum with 1.9% but failed the rupture life and 10% rupture elongation requirement with 31.6 hr and 5.6%. Fracture face and metallographic examination of both specimens revealed no microshrinkage or microstructural differences between the two specimens to account for the extreme difference in creep properties. Split results were also obtained with the creep/stress rupture test and retest of two DS Mar-M200 + Hf specimens with the 1.0% prestrain prior to the rejuvenation cycle. The first specimen tested met the 20 hr creep and rupture life requirements but fell short of the minimum rupture elongation with 8.3%. The retest, however, met all test requirements and compared to the standard heat treatment results exhibited an increase in rupture life from 42.5 to 64.0 hr and a decrease in 20 hr creep strain from 1.8 to 1.05%. The rupture elongation, however, was reduced from 20.5 to 12.1% for the prestrain plus rejuvenation retest as compared to the standard heat treatment test. As before, fracture face and microstructure examination was unable to find cause for the data scatter between the two tests.

The number of specimens tested to determine the effects of thermal rejuvenation on mechanical property requirements of CC IN 100 and DS Mar-M200 + Hf were limited and as a consequence the results are somewhat inconclusive. However, based on the preceding discussion, it is indicated that rejuvenation heat treatments can be applied after at least 1.0% of induced creep strain without seriously degrading the required mechanical properties for both alloys below their respective specification limits. The reduction in 1400°F ductility for CC IN 100 and 1800°F/32 ksi ductility for DS Mar-M200 + Hf was the most limiting result observed; however, this might be improved by optimization of the rejuvenation heat treatments or might be acceptable to engine use in view of the improved creep properties for CC IN 100 and DS Mar-M200 + Hf at 1650° and 1800°F, respectively.

Rejuvenation Confirmation

In the previous discussion under rejuvenation heat treatment selection it was noted that CC IN 100 specimens rejuvenated after the 1.0% prestrain exhibited increased prior creep elongation compared to nonrejuvenated baseline specimens, while rejuvenated DS MAR-M200 + Hf specimens exhibited superior creep rupture life as compared to baseline specimens. It is reasonable to conclude that 100% reversal of the physical and microstructural damage induced by the 1.0% prestrain test would result in the recovery of only the 1.0% strain and life of the prestrain test. Therefore, any further property increase must be attributed to effects of the rejuvenation heat treatments. Rejuvenation heat treatment effects must also be considered as the cause for the decrease in prior creep strain for rejuvenated DS MAR-M200 + Hf.

These conclusions questioned whether the rejuvenation heat treatments were completely healing physical strain damage (dislocation pile-ups, microvoids, etc.) or merely modifying the microstructure sufficiently to produce the observed properties with only partial or no reversal of physical damage. In an effort to answer this question a test evaluation was performed in which the rejuvenation heat treatments were substituted for the initial standard heat treatments and a series of creep tests were conducted in a manner similar to those conducted during the rejuvenation heat treatment selection. The Figure 24 flow chart illustrates the test schedule utilized which included continuous and interrupted baseline tests as well as specimens prestrained to 1.0% and retested to failure after thermal rejuvenation.

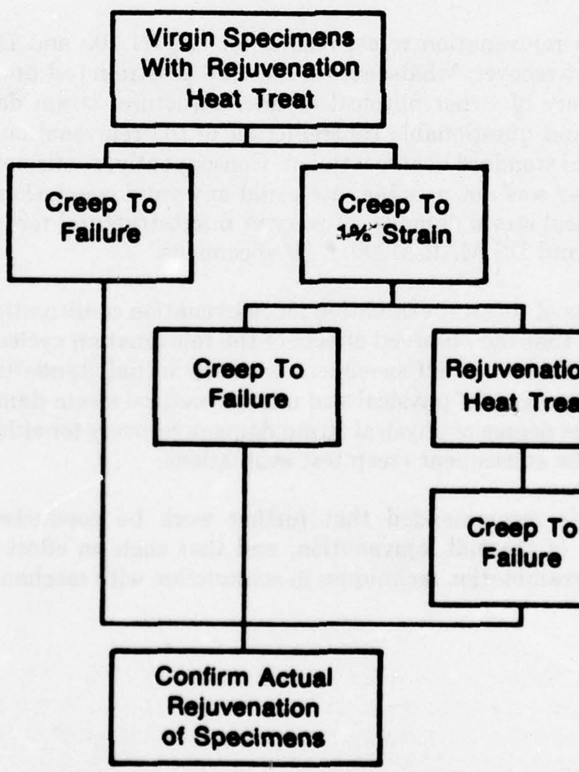

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Figure 24. Test Schedule 4, Rejuvenation Confirmation

As the initial heat treatment and the rejuvenation heat treatment following the 1.0% prestrain are the same in this evaluation, 100% rejuvenation of the prestrain induced physical and microstructural creep damage could be confirmed if the rejuvenated retest results were equivalent to the baseline results.

The results of these tests are tabulated in Tables 6 and 7 and are plotted in Figures 25 and 26. Because the numbers of specimens available for these tests were limited, the results were, in many cases, inconclusive because of the degree of data scatter encountered.

In Figures 25 and 26 the results of continuous and interrupted baseline tests and of rejuvenated specimen retests are compared for CC IN 100 and DS MAR-M200 + Hf with the two initial heat treatments; rejuvenation and standard. No improvement in rupture life was noted for CC IN 100 with the initial rejuvenation heat treatment although a possible increase in prior creep strain was indicated for the continuous baseline tests. In addition, the agreement between continuous and interrupted baseline results were not as close as earlier noted for specimens with the standard heat treatment. Similarly, little agreement was noted between continuous and interrupted baseline tests with DS MAR-M200 + Hf specimens initially heat-treated to the rejuvenation cycle parameters; however, a dramatic improvement in rupture life was noted with continuous baseline specimens with the initial rejuvenation heat treatment. Conversely, a decrease in prior creep strain was indicated by the continuous baseline results of specimens initially heat-treated to the rejuvenation cycle as compared to the baseline results for DS MAR-M200 + Hf specimens with the initial standard heat treatment.

The prestrain plus rejuvenation retest results for CC IN 100 and DS MAR-M200 + Hf unaccountably showed no recovery whatsoever of the 1.0% prestrain test properties. These results indicated that no recovery of either physical or microstructural strain damage had occurred, which was a complete and questionable contradiction to the rejuvenation results observed for specimens with the initial standard heat treatment. Consequently, confirmation of 100% recovery of physical strain damage was not possible, nor could any valid conclusions be drawn as to the relative degrees of physical strain damage recovery vs microstructural recovery/modification for rejuvenated CC IN 100 and DS MAR-M200 + Hf specimens.

Although the results of this test evaluation for rejuvenation confirmation were inconclusive, it should be pointed out that the observed effects of the rejuvenation cycles on 1.0% prestrained CC IN 100 and DS MAR-M200 + Hf specimens with the initial standard heat treatment was effectively that of 100% recovery of physical and microstructural strain damage. In addition, the inability to determine the degree of physical strain damage recovery for either alloy had no effect on the performance of the subsequent creep test evaluations.

In conclusion, it is recommended that further work be conducted to determine the controlling mechanisms of thermal rejuvenation, and that such an effort should fully employ current metallographic examination techniques in conjunction with mechanical property testing.

TABLE 6. CC IN 100 CREEP TEST DATA FOR SPECIMENS WITH AN INITIAL REJUVENATION HEAT TREATMENT, 1650°F/40 ksi

	1.0% Prestrain Test			*Retest to Failure*			*Prestrain and Retest Totals*		
Test Group Identification	*Initial Heat Treatment (hr)*	*Time to 1.0% Strain (hr)*	*Rejuvenation Heat Treatment (hr)*	*Time to 1.0% Strain (hr)*	*Time to Rupture (hr)*	*Prior Creep Strain (%)*	*Creep Strain (%)*	*Rupture Life (hr)*	*Rupture Elong. (%)*
Continuous Baseline	2025°F/4	71.8	—	6	*155.6	7.62	8.62	227.4	8.9
	1600°F/12	104.1	—	7	*189.7	9.90	10.90	293.8	11.3
	Air cool								
Average		88.0	—	7	*172.7	8.76	9.76	260.6	10.1
Interrupted Baseline	2025°F/4	91.9	None	52.3	144.3	6.01	7.01	236.2	7.4
	1600°F/12	72.4	None	57.1	162.3	7.15	8.15	234.7	8.5
	Air cool								
Average		82.2		54.7	153.3	6.58	7.58	235.5	8.0
Rejuvenated	2025°F/4	98.1	2025°F/4	59.0	157.6	7.84	8.84	255.7	9.7
	1600°F/12	75.1	1600°F/12	61.2	165.6	7.00	8.00	240.7	9.1
	Air cool		Air cool						
Average		86.6		60.6	161.6	7.42	8.42	248.2	9.4

*Rupture Life − 1.0% life

TABLE 7. DS MAR-M200 + Hf CREEP TEST DATA FOR SPECIMEN WITH AN INITIAL REJUVENATION HEAT TREATMENT, 1800°F/28 ksi

	1.0% Prestrain Test			*Retest to Failure*			*Prestrain and Retest Totals*		
Test Group Identification	*Initial Heat Treatment (hr)*	*Time to 1.0% Strain (hr)*	*Rejuvenation Heat Treatment (hr)*	*Time to 1.0% Strain (hr)*	*Time to Rupture (hr)*	*Prior Creep Strain (%)*	*Creep Strain (%)*	*Rupture Life (hr)*	*Rupture Elong. (%)*
Continuous Baseline	2200°F/10	57.0		—	*107.6	15.9	16.9	164.6	22
	2250°F/4	66.0		—	* 90.6	9.0	10.0	156.6	11
	1975°F/4								
	1600°F/32								
	Fast air cool								
Average		61.5			* 99.1	12.5	13.5	160.6	16.5
Interrupted Baseline	2200°F/10	41.0	None	40.2	93.3	11.1	12.1	136.4	13.5
	2250°F/4	54.3	None	21.5	27.5	1.3	2.3	83.3	2.9
	1975°F/4								
	1600°F/32								
	Fast air cool								
Average		47.7		30.9	60.4	6.2	7.2	109.9	8.2
Rejuvenated	2200°F/10	44.4	2200°F/10	34.6	78.3	6.8	7.8	122.7	9.9
	2250°F/4	44.6	2250°F/4	33.0	77.8	8.2	9.2	124.8	11.8
	1975°F/4		1975°F/4						
	1600°F/32		1600°F/32						
	Fast air cool		Fast air cool						
Average		44.5		33.8	78.1	7.5	8.5	123.8	10.9

*Rupture Life − 1.0% life

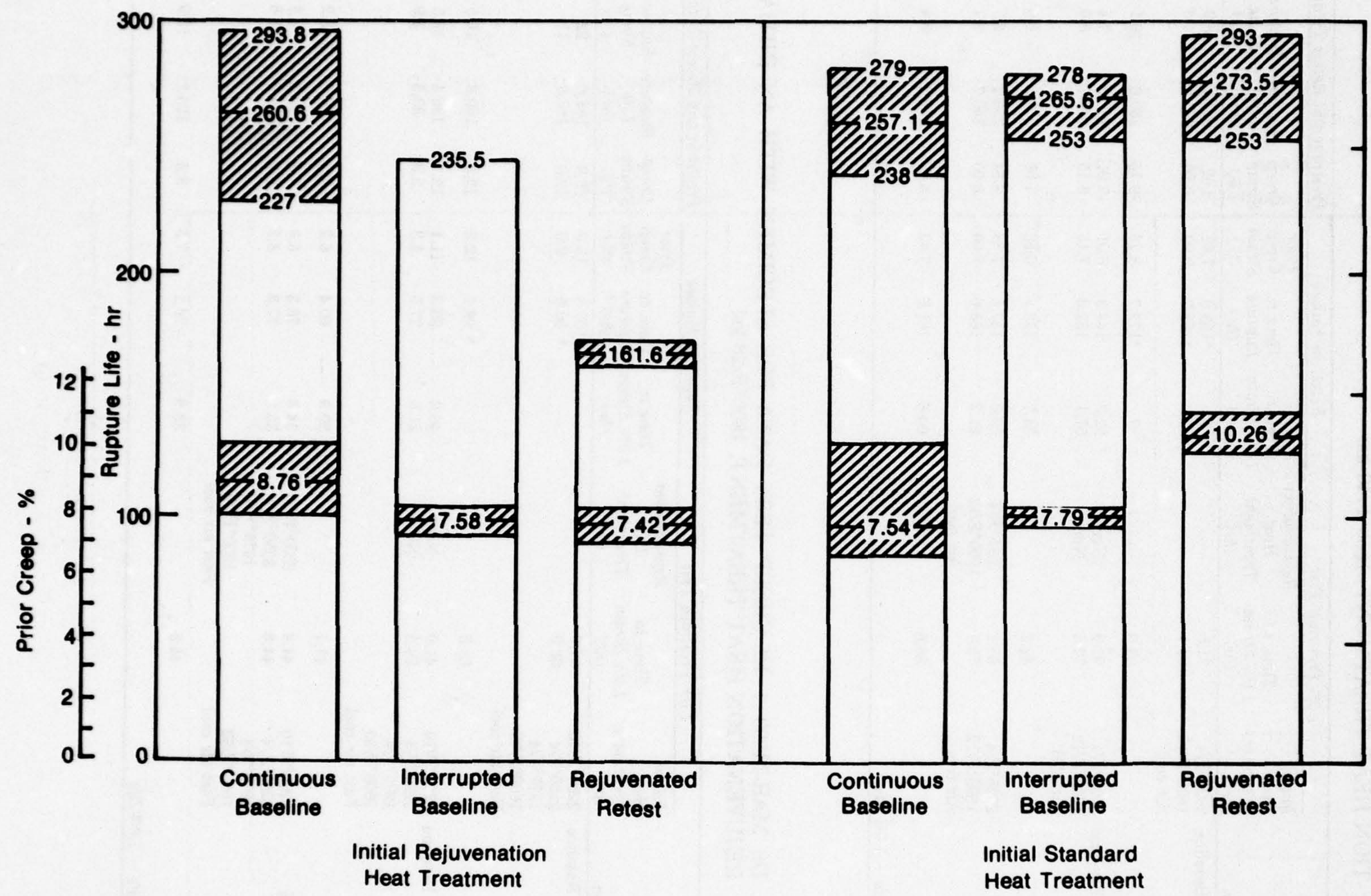

Figure 25. Initial Standard Heat Treatment vs Initial Rejuvenation Heat Treatment for CC IN 100 at 1650°F/40 ksi

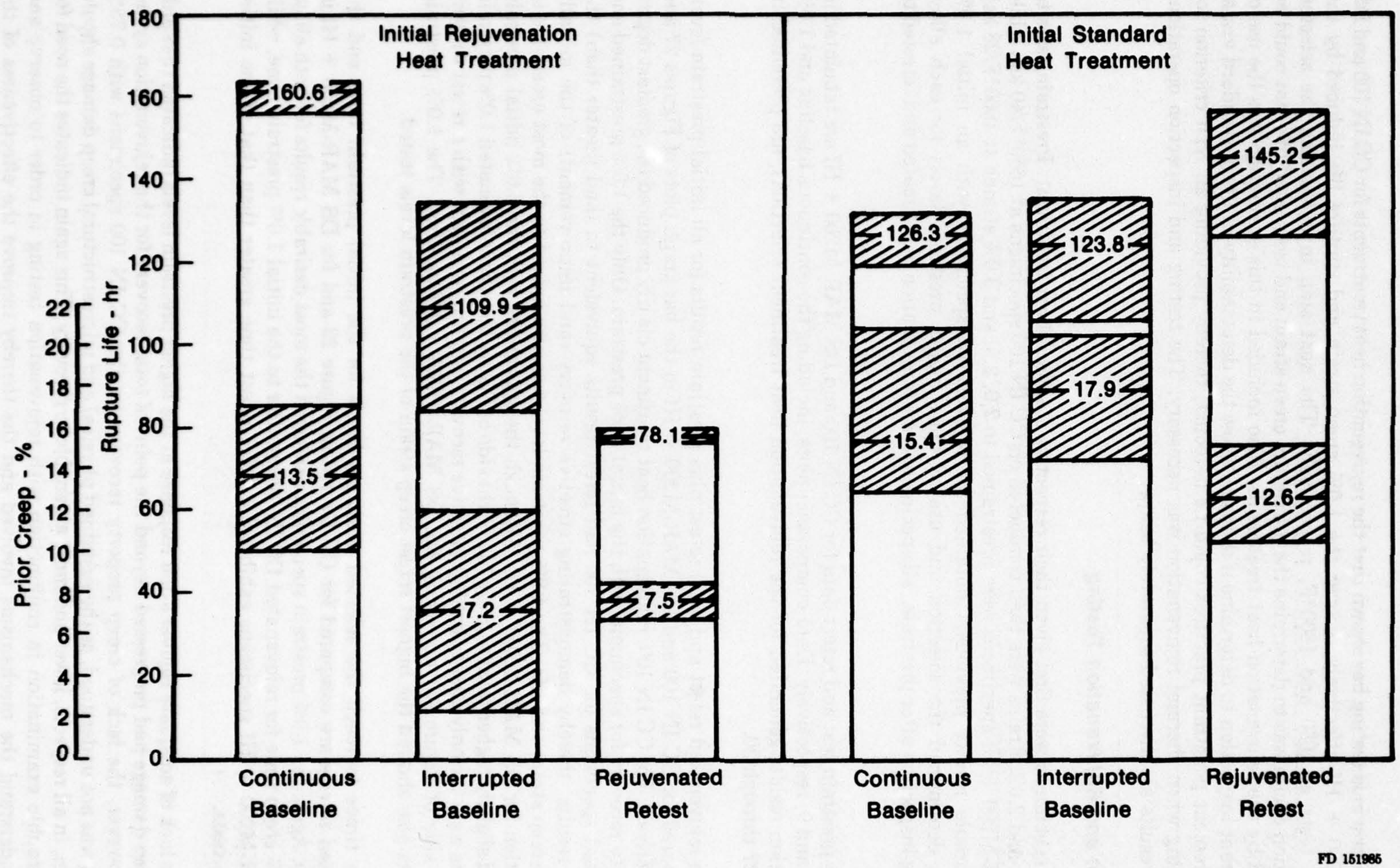

Figure 26. Initial Standard Heat Treatments vs Initial Rejuvenation Heat Treatment for DS MAR-M200 + Hf at 1800°F/28 ksi

Determination of the Maximum Recoverable Creep Strain

The previous testing has shown that the rejuvenation heat treatments for CC IN 100 and DS MAR-M200 + Hf effectively recover the 1.0% creep strain and rupture life induced by the prestrain tests at 1650 and 1800°F, respectively. The next step in evaluating the selected rejuvenation cycles was to determine the maximum creep strain and associated life that could be recovered by the rejuvenation heat treatments. Also included in this evaluation was the use of eddy current inspection to determine if damage below the detectability limits of standard visual and fluorescent penetrant practices could be detected, thereby providing an NDI criterion for determining when thermal rejuvenation was necessary. The testing and inspection operations and the results are discussed separately below.

Prestrain and Rejuvenation Testing

All specimens were first given their respective standard heat treatment. Prestrain tests to 0.75, 1.5, and 2.0% strains were then conducted on CC IN 100 specimens at 1650°F/40 ksi, while DS MAR-M200 + Hf specimens were prestrained to 2.0, 2.5, and 3.0% strains at 1800°F/28 ksi. The favorable results previously obtained for rejuvenated specimens with an initial 1.0% prestrain determined the selection and use of these higher prestrain levels for each alloy. Following inspection after prestrain, all specimens were rejuvenation heat-treated and retested to failure.

The prestrain test and retest data for CC IN 100 and DS MAR-M200 + Hf are tabulated in Tables 8 and 9, respectively. Data comparison plots, including the continuous baseline and 1.0% rejuvenation results generated for the rejuvenation heat treatment selections, are presented in Figures 27 through 30.

The rejuvenated retest and total retest plus prestrain results for all initial prestrain levels are compared for CC IN 100 and DS MAR-M200 + Hf in the bar graph plots of Figures 27 and 28, respectively. For CC IN 100, rejuvenation heat treatment clearly produced the greatest degree of property recovery for specimens with the initial 1.0% prestrain. Only the 1.0% prestrained and rejuvenated specimens for CC IN 100 had retest results equivalent to (and greater than) the baseline results, thereby demonstrating effective recovery (and improvement) of the initially induced creep strain and life. The 1.0% prestrain level was also judged to the most amenable to rejuvenation for DS MAR-M200 + Hf. Although the specimens with the 3.0% initial prestrain exhibited slightly higher total rupture life (right side of Figure 28), the rejuvenated 1.0% prestrain specimens were the only ones to exhibit effective recovery and improvement with a retest rupture life (left side of Figure 28) exceeding the DS MAR-M200 + Hf baseline. The 1.0% prestrain specimens also showed the highest retest creep strain of the prestrain levels tested.

The times to reach the selected prestrain levels for the initial prestrain tests and the rejuvenated retests are compared for CC IN 100 in Figure 29 and for DS MAR-M200 + Hf in Figure 30. Again the 1.0% prestrain specimens exhibited the most desirable results for both alloys with 1.0% creep time for rejuvenated CC IN 100 similar to the initial 1.0% prestrain time, while DS MAR-M200 + Hf specimens exhibited a 1.0% retest time greater than that of the initial prestrain tests.

The lack of adequate rejuvenation response at the higher prestrain levels indicated that 3rd-stage creep damage had progressed beyond the point of total recovery for the rejuvenation cycles used. However, the lack of creep property recovery for the CC IN 100 specimens with 0.75% prestrain was not understood, as the sustained physical and microstructural creep damage should have been, in all respects, lower and more amenable to recovery. This again indicates the need for metallographic examination in conjunction with rejuvenation testing in order to observe and better understand the mechanisms involved and the thereby improve the effectiveness of the rejuvenation heat treatments.

TABLE 8. CC IN 100 CREEP TEST DATA FOR REJUVENATED SPECIMENS WITH VARIOUS INITIAL CREEP PRESTRAINS, 1650°F/40 ksi

	Prestrain Test			Retest to Failure			Prestrain and Retest Totals		
Test Group Identification	*Initial Heat Treatment (hr)*	*Time to 1.0% Strain (hr)*	*Rejuvenation Heat Treatment (hr)*	*Time to % Strain (hr)*	*Time to Rupture (hr)*	*Prior Creep Strain (%)*	*Creep Strain (%)*	*Rupture Life (hr)*	*Rupture Elong. (%)*
0.75% Prestrain	1975°F/8	60.1	2025°F/4	37.9	162.4	10.30	11.05	222.5	11.5
	1600°F/12	49.3	1600°F/12	43.8	185.7	11.20	12.01	235.0	12.5
	Air cool	65.7	Air cool	46.6	143.8	11.91	12.67	259.5	13.0
Average		58.4		42.8	180.6	11.14	11.91	239.0	12.3
1.5% Prestrain	1975°F/8	134.9	2025°F/4	83.4	188.1	8.74	10.26	323.0	10.3
	1600°F/12	160.6	1600°F/12	60.5	177.7	10.25	11.75	338.3	11.5
	Air cool	163.1	Air cool	59.6	118.3	6.17	7.77	281.4	7.8
Average		152.9		67.8	161.4	8.39	9.93	314.2	9.9
2.0% Prestrain	1975°F/8	122.7	2025°F/4	63.0	136.4	9.60	11.60	259.1	12.2
	1600°F/12	133.5	1600°F/12	92.5	178.6	8.75	10.75	312.1	11.0
	Air cool	142.4	Air cool	48.4	59.5	3.14	5.14	201.9	5.0
Average		132.9		68.0	124.8	7.16	9.16	257.7	9.4

TABLE 9. DS MAR-M200 + Hf CREEP TEST DATA FOR REJUVENATED SPECIMENS WITH VARIOUS INITIAL CREEP PRESTRAINS, 1800°F/28 ksi

	Prestrain Test			Retest to Failure			Prestrain and Retest Totals		
Test Group Identification	*Initial Heat Treatment (hr)*	*Time to % Strain (hr)*	*Rejuvenation Heat Treatment (hr)*	*Time to % Strain (hr)*	*Time to Rupture (hr)*	*Prior Creep Strain (%)*	*Creep Strain (%)*	*Rupture Life (hr)*	*Rupture Elong. (%)*
2.0% Prestrain	2200°F/2	41.4	2200°F/10	50.0	79.4	8.6	10.6	122.1	10.7
	1975°F/4	55.1	2250°F/4	57.6	101.7	13.0	15.1	159.4	16.9
	1600°F/32	67.3	1975°F/4	36.0	69.4	13.2	15.2	137.2	17.4
	Air cool		1600°F/32						
			Fast air cool						
Average		54.6		47.9	83.5	11.6	13.6	139.6	15.0
2.5% Prestrain	2200°F/2	74.6	2200°F/10	15.1	28.3	14.2	16.7	102.9	20.8
	1975°F/4	69.6	2250°F/4	68.2	102.6	8.6	11.1	172.2	11.9
	1600°F/32	69.7	1975°F/4	49.3	73.1	8.2	10.7	142.8	13.2
	Air cool		1600°F/32						
			Fast air cool						
Average		71.3		44.2	68.0	10.3	12.8	139.3	15.3
3.0% Prestrain	2200°F/2	68.3	2200°F/10	76.0	108.3	12.2	15.2	176.6	16.9
	19750F/4	77.1	2250°F/4	73.7	120.4	10.3	13.3	198.3	23.0
	1600°F/32	74.8	1975°F/4	65.8	92.9	9.3	12.3	169.8	16.6
	Air cool		1600°F/32						
			Fast air cool						
Average		73.4		71.8	107.2	10.6	13.6	181.6	18.8

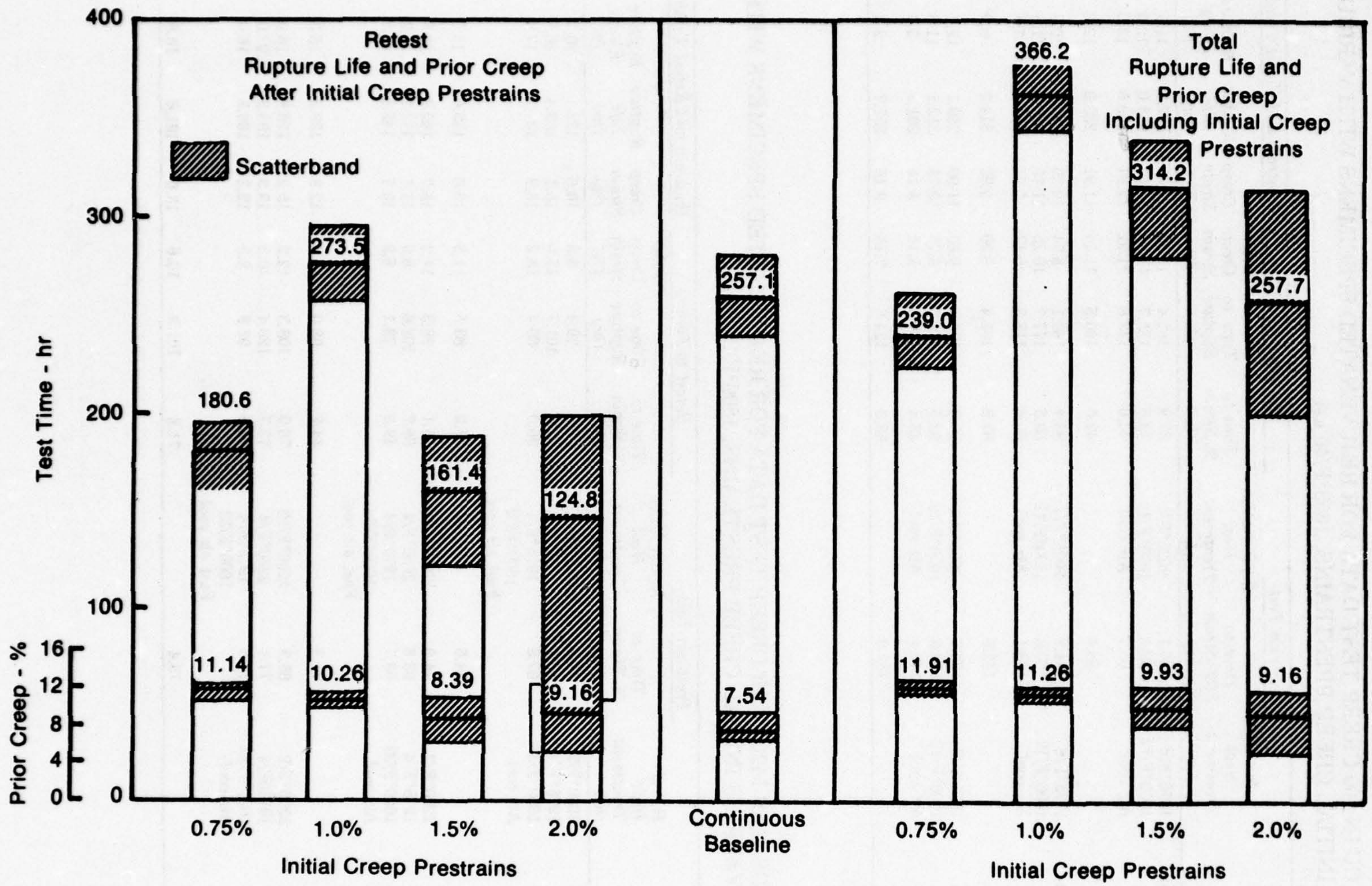

Figure 27. CC IN 100 Creep Properties Comparison for Rejuvenated Specimens With Various Creep Prestrains, 1650°F/40 ksi

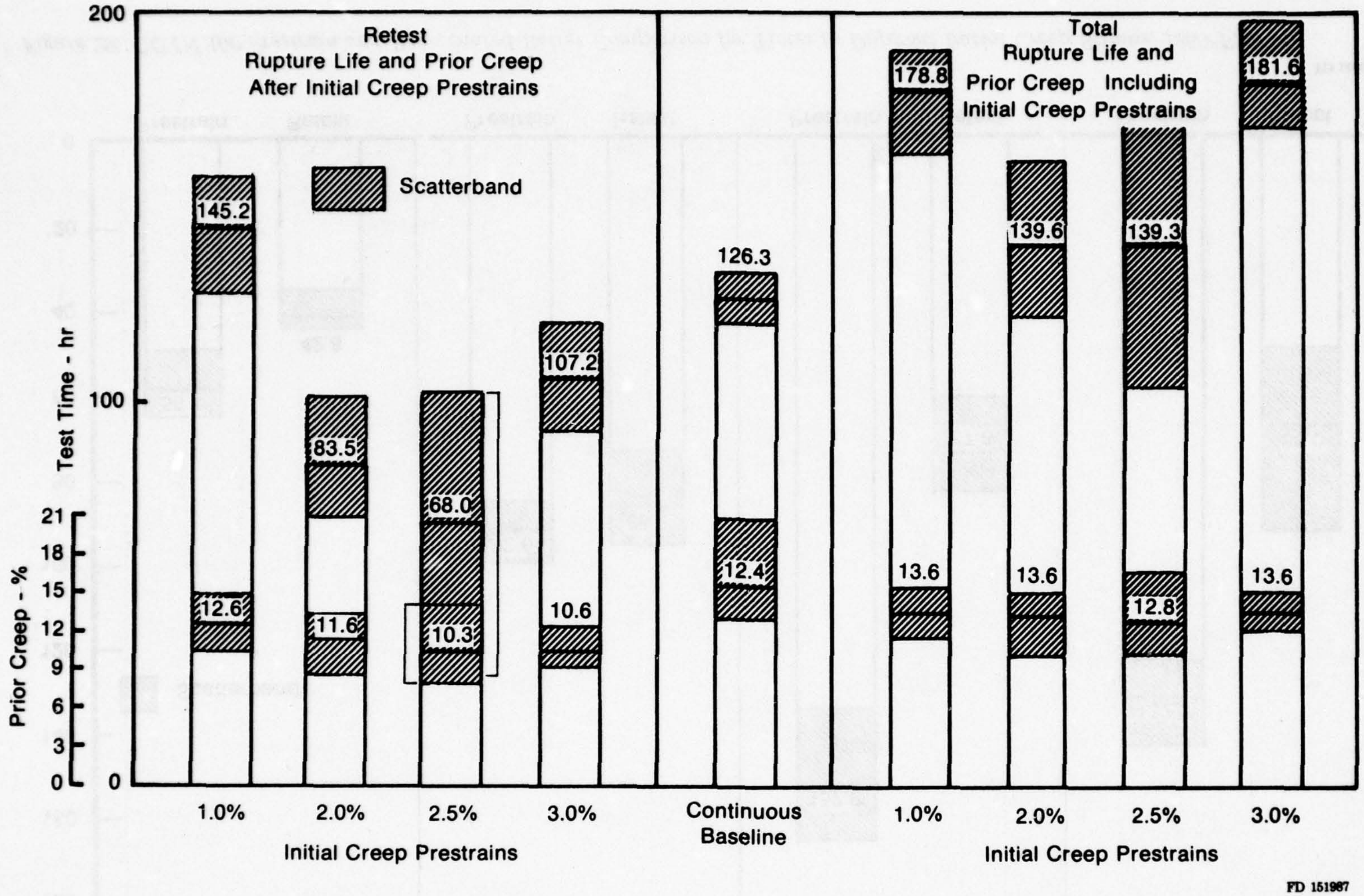

Figure 28. DS MAR-M200 + Hf Creep Properties Comparison for Rejuvenated Specimens With Various Creep Prestrains, 1800°F/28 ksi

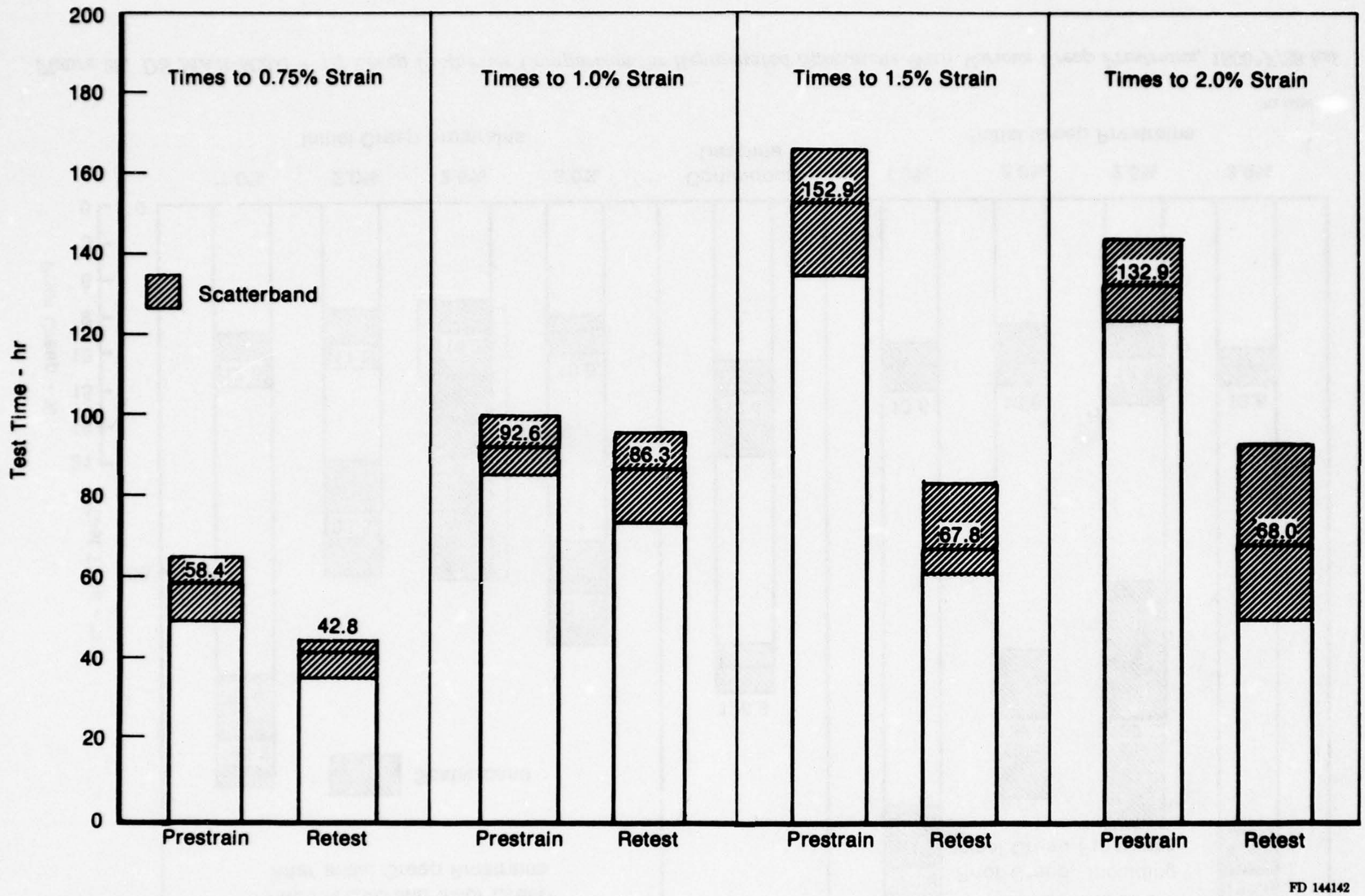

Figure 29. CC IN 100 Prestrain and Rejuvenated Retest Comparison for Times to Different Initial Creep Strains, 1650°F/40 ksi

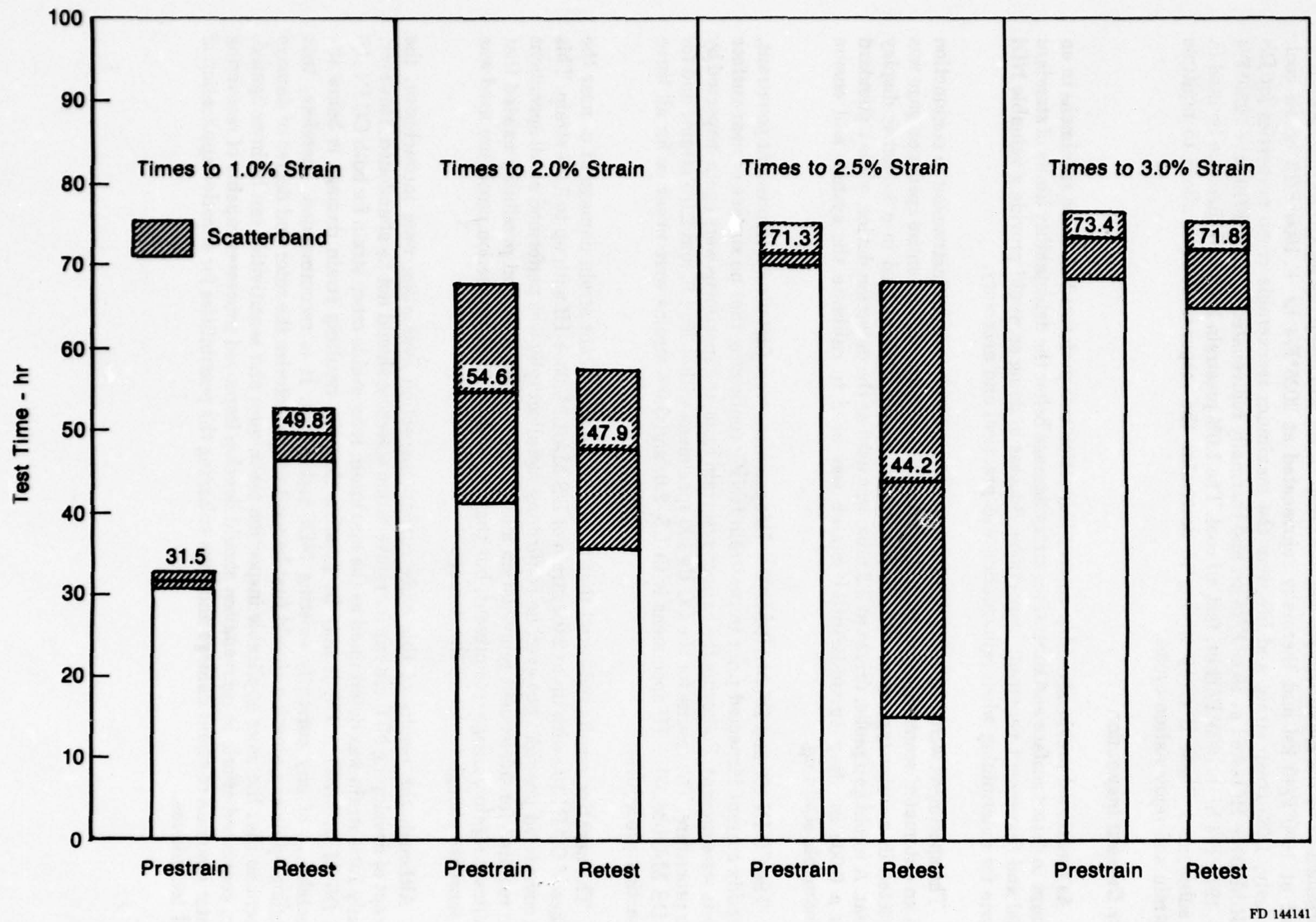

Figure 30. DS MAR-M200 + Hf Prestrain and Rejuvenated Retest Comparison for Times to Different Initial Creep Strains, 1800°F/28 ksi

Based on the results of this test evaluation, 1.0% strain and its associated life were determined to be the maximum recoverable creep strain and creep life for CC IN 100 specimens tested at 1650°F/40 ksi and thermally rejuvenated at 2025°F/4 hr + 1600°F/12 hr air cool. Similarly, 1.0% creep strain and life were the maximum recoverable creep properties for DS MAR-M200 + Hf tested at 1800°F/28 ksi and thermally rejuvenated at 2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr, fast air cool. The 1.0% prestrain level will therefore be used in the subsequent Phase II creep testing to determine the response of both alloys to multiple prestrain and rejuvenation cycles.

Eddy Current Inspection

As mentioned previously, eddy current inspection was performed on these specimens in an attempt to detect surface and subsurface strain damage below the detectability limits of standard visual and fluorescent penetrant inspections. Success in doing so would provide a valuable NDI criteria for determining when rejuvenation was practical and necessary.

The specimens were inspected using a conventional eddy current instrument in conjunction with an automated scanning apparatus, diagrammed in Figure 31. The entire specimen gage was inspected in a roster-type scan and the inspection results were plotted in a isometric display format. A toroid gap probe, driven at 3.2 mhz, was used as the detection device, while a standard with a 0.008 in. deep circumferential scratch was used to calibrate the system and ensure reproducible scanning.

The CC IN 100 and DS MAR-M200 + Hf specimens were first visual, fluorescent penetrant, and eddy current inspected prior to prestrain testing confirming that no surface or near-surface defects were present. Following the various prestrain tests, the specimens were again inspected by each procedure. The results for the CC IN 100 specimens with 0.75, 1.5, and 2.0% strains and for the DS MAR-M200 + Hf specimens with 1.5, 2.0, and 3.0% strains were negative for all three inspection procedures.

The negative results indicated that there was no significant strain damage at or near the surface of CC IN 100 with up to 2.0% strain or DS MAR-M200 + Hf with up to 3.0% strain. This was considered possible; however, no confirming metallography was performed as all specimens were required for subsequent rejuvenation and failure testing. A second possibility existed that significant strain damage was present, but that the eddy current inspection procedure used was not sensitive enough to detect the damage.

Although the results of this eddy current inspection evaluation were inconclusive, the concept of developing NDI criteria for rejuvenation selection should not be abandoned. However, as only 1.0% strain was determined as the maximum recoverable creep strain for both CC IN 100 and DS MAR-M200 + Hf, it may be possible that the resulting strain damage is below the detectability of any currently existing NDI technology. It is recommended, therefore, that metallographic examination should first be used to characterize the rotor and degree of damage present so that the most applicable inspection techniques and sensitivities can be investigated. Also, continued efforts in rejuvenation should develop improved processes capable of recovering greater amounts of strain damage and thus enlarging the possibilities for effective application of NDI techniques.

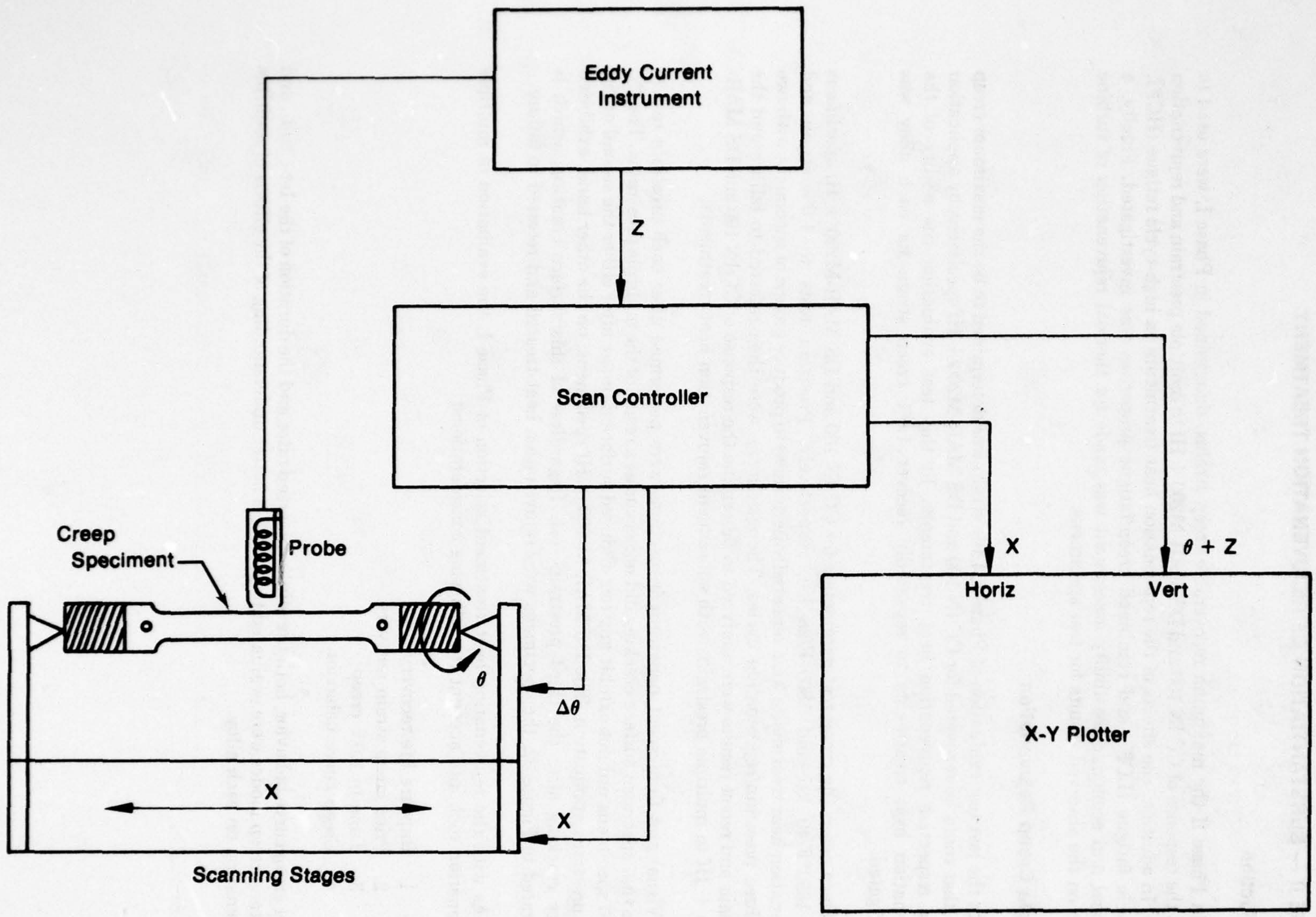

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Figure 31. Raster Scanning Apparatus for Automated Eddy Current Inspection of Creep Specimens

PHASE II — SUBSTANTIATION OF REJUVENATION TREATMENT

Introduction

In Phase II the maximum recoverable creep strains, determined in Phase I, were used to assess the response of CC IN 100 and DS MAR-M200 + Hf to multiple prestrain and rejuvenation cycles. In addition, the effects of the rejuvenation heat treatments on high-cycle fatigue (HCF), low-cycle fatigue (LCF), and combined creep/fatigue properties was investigated. Finally, a technical and economic feasibility assessment was made for thermal rejuvenation of turbine blades on the observed results for test specimens.

Multiple Creep Rejuvenation

In the last test evaluation of Phase I, 1.0% strain was determined to be the maximum creep strain that could be recovered for CC IN 100 and DS MAR-M200 + Hf specimens by application of the respective rejuvenation heat treatments. In this test evaluation the ability of the rejuvenation heat treatments to repeatedly recover 1.0% creep strain for each alloy was investigated.

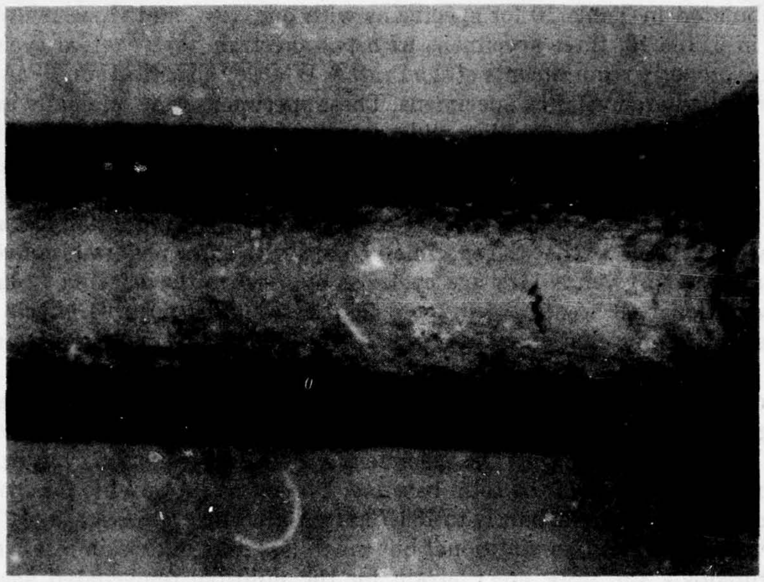
Once again the creep test parameters for CC IN 100 and DS MAR-M200 + Hf specimens were 1650°F/40 ksi and 1800°F/28 ksi, respectively. Prestrain tests to 1.0% strain and rejuvenation heat treatments were repeatedly performed to produce groups of specimens with two and three prestrain/rejuvenation cycles. The specimens were then retested to failure and the prestrain and retest results were analyzed to determine the response of CC IN 100 and DS MAR-M200 + Hf to multiple prestrains with subsequent rejuvenation heat treatments.

Visual and fluorescent penetrant inspections were performed after each prestrain test to assure that specimen surface cracking did not occur as a result of the multiple prestrains. The CC IN 100 specimens did not exhibit any test-induced surface damage after either the second or the third prestrain application. The DS MAR M-200 + Hf specimens, on the other hand, exhibited surface cracking after the third prestrain test. Regardless of this surface cracking, which is illustrated in Figure 32, the specimens were rejuvenation heat-treated and retested to failure.

As with the rejuvenation heat treatment selection of Phase I, the evaluation of multiple rejuvenation took into account the following considerations:

1. Rupture life recovery
2. Prior creep strain recovery
3. Time to 1.0% creep
4. Creep curve behavior.

Under creep curve behavior, both the minimum creep rates and the duration of the 1st-, 2nd-, and 3rd-stage creep modes were evaluated to provide a better understanding of the effects of multiple rejuvenation on each alloy.



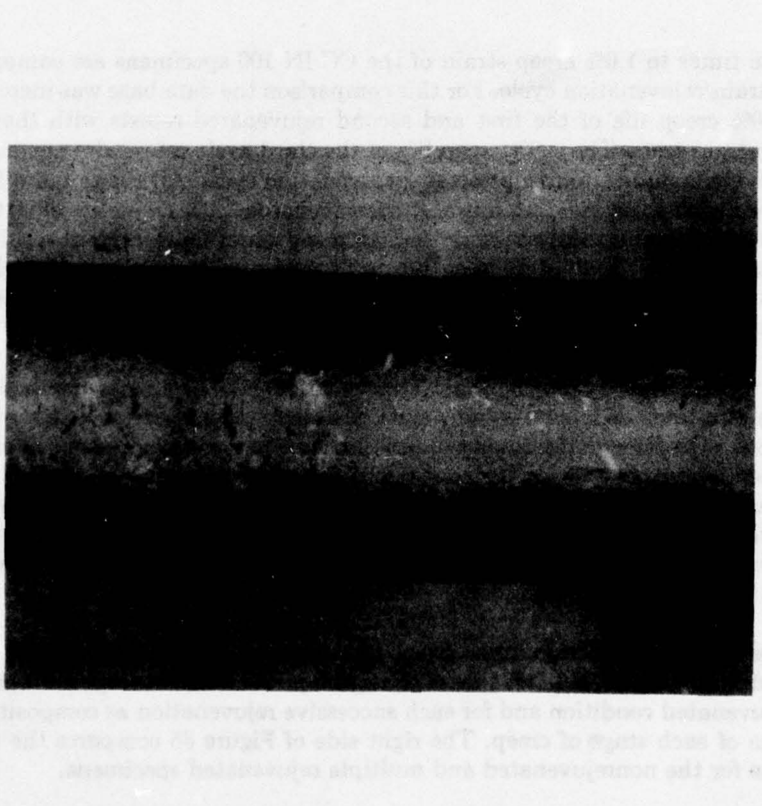


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Figure 32. DS MAR-M200 + Hf Specimen Cracking After Three 1.0% Prestrain/Rejuvenation Heat Treatment Cycles, 1650°F/40 ksi

CC IN 100 Results

The CC IN 100 prestrain results, retest to failure results, and total creep test (prestrain + retest) results are tabulated in Table 10 for specimens with one, two, and three rejuvenation cycles. As indicated in Table 10, three specimens with two prestrain/rejuvenation cycles were tested to the minimum property requirements of the Pratt & Whitney specification, PWA 658, as was done in Phase I for singly rejuvenated specimens. These specimens were originally intended to be used for data backup in the event that wide data scatter or inconclusive results were obtained. However, the data scatter was tight and the results were conclusive, so the extra specimens with two rejuvenation cycles were tested to supplement the mechanical properties requirements testing of Phase I. The results of these tests will be more appropriately discussed later. It is also indicated in Table 10 that the specimen groups with three prestrain/rejuvenation cycles was inadvertently given given a 14hr age cycle, as opposed to the selected 12-hr cycle, during the last rejuvenation heat treatment prior to final retest. The possible effects of this additional aging time on the rejuvenation response of CC IN 100 are also discussed later.

The rejuvenated retest properties (excluding the 1.0% prestrain) and the total creep test properties (including the 1.0% prestrain) for CC IN 100 are plotted in Figure 33 with the corresponding Phase I baseline results. Only the specimens with one rejuvenation cycle exhibited retest rupture life equivalent to that of the total baseline. The retest rupture life for specimens with two rejuvenation cycles decreased sharply to 183.7 hr from the one cycle average of 273.5 hr. The three cycle specimens exhibited an additional but much less drastic drop in retest rupture life to 163.9 hr. Surprisingly the prior creep strain for the multiple rejuvenated specimens remained relatively constant with 10.26% for one rejuvenative, dropping to 9.10% for two rejuvenations, and rising to 10.21% for three rejuvenations. These pretest results made the total rupture lives and creep strains for each rejuvenation group essentially equivalent at 366.2 hr and 11.26%, 342.7 hr and 11.10%, and 369.8 hr and 13.21% for one, two, and three rejuvenation cycles, respectively.

In Figure 34 the times to 1.0% creep strain of the CC IN 100 specimens are compared for each successive prestrain/rejuvenation cycle. For this comparison the data base was increased by incorporating the 1.0% creep life of the first and second rejuvenated retests with that of the second and third prestrain tests. The 1.0% creep life of the third cycle retest also expanded the comparison to effectively include a fourth prestrain/rejuvenation cycle. All Phase I and Phase II prestrain results were averaged to yield an initial, nonrejuvenated 1.0% creep life of 90.0 hr. As seen in Figure 34, the second and third prestrain test after rejuvenation treatment resulted in a 17% and 47% decrease of the initial 1.0% creep life to 74.5 hr and 48.1 hr, respectively. This accelerating decrease, however, slowed to 49% (45.7 hr) for the fourth prestrain (1.0% creep life of the third retest) after rejuvenation.

To understand what repeated rejuvenation cycles were doing to the creep curve behavior of CC IN 100, both the durations of the 1st-, 2nd-, and 3rd-stage creep modes and the minimum (2nd-stage) creep mode rates were determined from the 1.0% creep curves for the specimens with one, two and three rejuvenations and for the continuous baseline specimens of Phase I. As the creep stage durations were graphically determined, the data should not be accepted as accurate on an individual basis because of the double interpretative process involved in constructing the curve plus determining creep mode boundaries. However, for the purpose of relative comparison between test groups the data may be considered valid.

The creep stage duration and minimum creep rate data are tabulated in Table 11 and graphically compared in Figure 35. The left side of the figure presents the average 1.0% creep life for the initial nonrejuvenated condition and for each successive rejuvenation as composite of the hours and percentage of each stage of creep. The right side of Figure 35 compares the average minimum creep rates for the nonrejuvenated and multiple rejuvenated specimens.

TABLE 10. CC IN 100 CREEP TEST DATA FOR SPECIMENS WITH MULTIPLE 1.0% PRESTRAINS AND REJUVENATION HEAT TREATMENTS, 1650°F/40 ksi

Test Group Identification	Prestrain Test Time to 1.0% Strain: First 1.0%* (hr)	Second 1.0%* (hr)	Third 1.0% (hr)	Prestrain Test Totals: Time (hr)	Strain (%)	*Retest to Failure: Time to 1.0% Strain (hr)	Time to Rupture (hr)	Prior Creep Strain (%)	Prestrain and Retest Totals: Creep Strain (%)	Rupture Life (hr)	Rupture Elongation (%)
One Rejuv Cycle	85.6	—	—	85.6	1.0	96.2	293.0	10.10	11.10	378.6	11.2
	93.2	—	—	93.2	1.0	88.4	253.3	9.89	10.89	346.5	11.3
	99.2	—	—	99.2	1.0	74.3	274.2	10.80	11.80	373.4	12.3
Average	92.6	—	—	92.6	1.0	86.3	273.5	10.26	11.26	366.2	11.6
Two Rejuv Cycles	91.1	73.2	—	164.3	2.0	—	***	—	—	—	—
	102.8	70.2	—	173.0	2.0	—	***	—	—	—	—
	78.1	73.1	—	151.2	2.0	—	***	—	—	—	—
	107.5	68.0	—	175.5	2.0	48.9	180.5	9.03	11.03	356.0	12.0
	80.6	63.7	—	144.3	2.0	51.5	191.7	8.96	10.96	336.0	12.4
	80.5	77.5	—	158.0	2.0	49.9	178.9	9.32	11.32	336.9	11.6
Average	90.1	71.0	—	161.1	2.0	50.1	183.7	9.10	11.10	342.7	12.0
Three Rejuv Cycles	105.0	74.5	45.3	224.8	3.0	**49.5	177.9	11.12	14.12	402.7	15.8
	74.0	69.3	47.3	190.6	3.0	**45.5	162.0	10.26	13.26	352.6	13.5
	90.5	66.0	45.7	202.2	3.0	**42.0	151.8	9.26	12.26	354.0	12.3
Average	89.8	69.5	46.1	205.9	3.0	45.7	163.9	10.21	13.21	369.8	13.9

* Rejuvenated at 2025°F/4 hr + 1600°F/12 hr – Air Cool
** 1600°F/14 hr Rejuvenation Age Cycle Instead of 1600°F/12 hr
*** Retests Performed at PWA 658 Specification Parameters

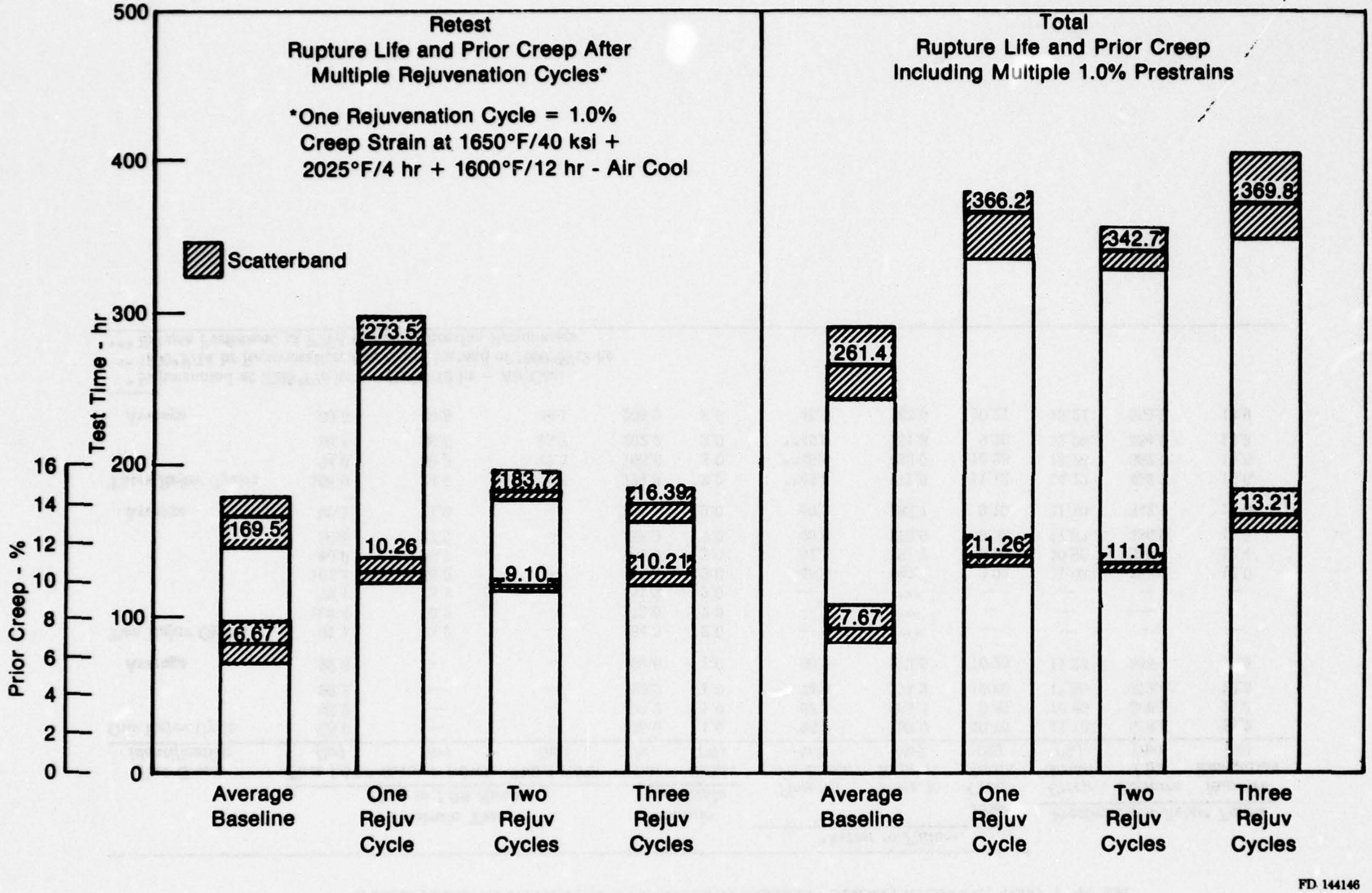


Figure 33. *Effect of Multiple Rejuvenation on CC IN 100 Creep Properties, 1650°F/40 ksi*

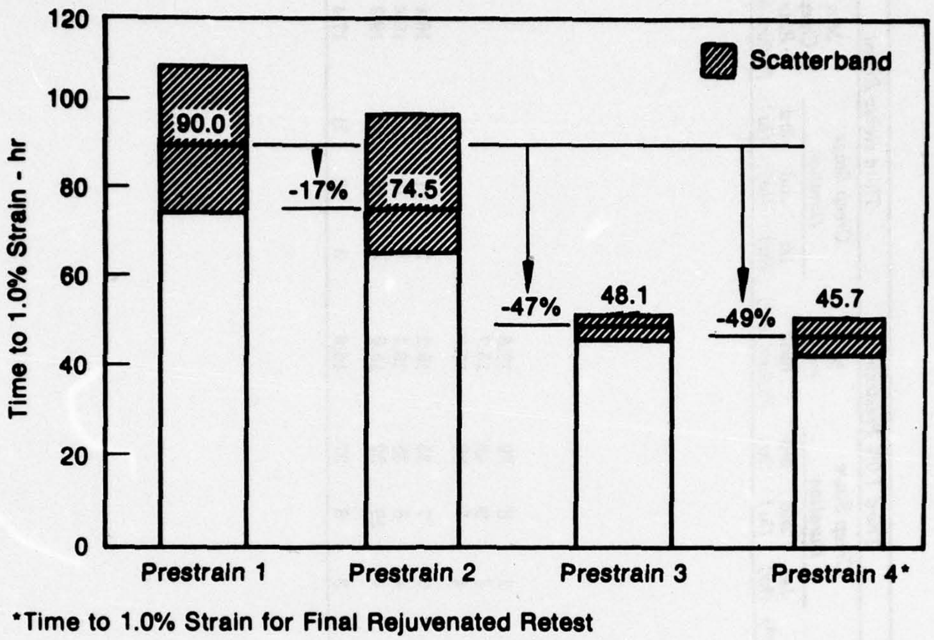
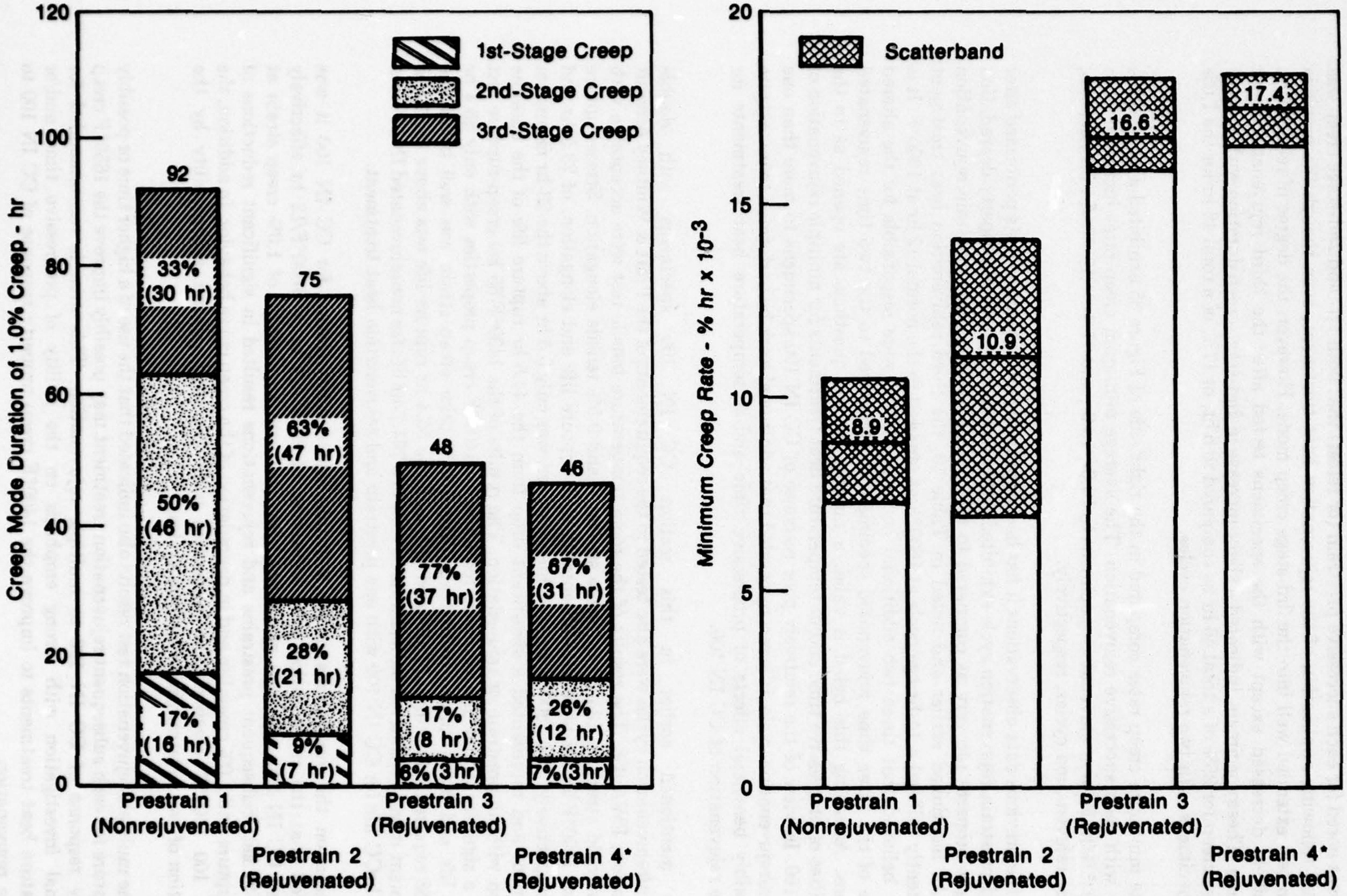


Figure 34. Effect of Multiple Rejuvenation on Time to 1.0% Creep Strain of CC IN 100, 1650°F/40 ksi

TABLE 11. CC IN 100 CREEP CURVE DATA FOR BASELINE AND REJUVENATED SPECIMENS, 1650°F/40 ksi

Test Group Identification	Initial 1.0% Prestrain: Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10^{-3})	Second 1.0% Prestrain: Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10^{-3})	Third 1.0% Prestrain: Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10^{-3})	Third Rejuv Retest: Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10^{-3})
Continuous Baseline	12	48	38	8.2												
	8	47	31	10.0												
	10	45	38	8.4												
One Rejuv Cycle	13	52	21	9.5	2	25	69	6.7								
	24	41	28	8.3	8	21	61	8.2								
	11	46	42	7.7	4	10	60	9.3								
Two Rejuv Cycles	15	45	31	8.1	8	23	42	11.2								
	15	51	37	7.4	6	26	38	12.1								
	22	38	18	10.0	6	23	44	13.2								
	20	40	48	8.0	10	17	31	11.3	2	8	39	17.8				
	15	45	21	10.1	8	19	37	14.0	3	9	40	15.7				
	21	35	25	9.9	8	20	50	10.2	4	7	39	15.8				
Three Rejuv Cycles	20	51	34	7.8	6	21	48	9.8	3	7	35	18.2	3	11	36	16.4
	15	49	10	10.5	7	23	39	13.2	4	8	35	16.1	3	12	31	16.4
	18	50	23	9.0	8	18	40	11.9	4	10	32	15.9	4	12	26	19.3
Average	16	46	30	8.9	7	21	47	10.9	3	8	37	16.6	3	12	21	17.4



*First 1.0% of Rejuvenated Retest

FD 144148

Figure 35. CC IN 100 1.0% Creep Curve Data Comparison for Specimens With Multiple Rejuvenations, 1650°F/40 ksi

It was noted for each successive prestrain (or retest) that both 1st- and 2nd-stage creep was reinitiated following application of the rejuvenation heat treatment, even though the previous prestrain test extended well into the 3rd-stage creep mode. However, the degree of reinitiation progressively decreased except with the specimens tested after the third rejuvenation heat treatments. These specimens indicated a slight increase in 2nd-stage creep duration with 12 hr of 2nd-stage creep for 26% of a total 46 hr as compared to 8 hr, or 17%, of a total 48 hr for the 1.0% life of specimens with two rejuvenation cycles.

The minimum creep rates compared in the right side of Figure 35 exhibited a progressive increase with each successive rejuvenation. The average minimum creep rates increased from 8.9×10^{-8} %/hr for nonrejuvenated specimens to 10.9-, 16.6-, and 17.4- $\times 10^{-8}$ %/hr for one, two, and three rejuvenation cycles, respectively.

In the previous data observations it has been repeatedly noted that the tests performed after the third prestrain/rejuvenation cycle exhibited either a reduced degree of property degradation or a slight property recovery as compared to test results following two prestrain/rejuvenation cycles. As mentioned earlier and noted in Table 10, the third rejuvenation heat treatment inadvertently utilized a 14-hr age cycle at 1600°F as opposed to the normal 12 hr at 1600°F. It is strongly believed that these two additional hours at 1600°F were responsible for the altered response of the three time rejuvenated specimens as compared to the two time rejuvenated specimens. Assuming this belief is valid, a number of new questions are opened as to the possibilities of progressive time and/or temperature heat treatments for multiple rejuvenation of CC IN 100. In view of the relatively poor response of CC IN 100 specimens to more than one prestrain/rejuvenation cycle, it is recommended that additional work be performed to investigate the possibly beneficial effects of progressive time and/or temperature heat treatments for multiple rejuvenation of CC IN 100.

As mentioned earlier in this section, CC IN 100 specimens with double prestrain/rejuvenation cycles were also tested to the requirements of the Pratt & Whitney Aircraft specification, PWA 658. The results of the room temperature tensile test were acceptable with 108.3 ksi yield strength, 135.2 ksi tensile strength, and 9.5% tensile elongation. Stress-rupture results at 1800°F/28 ksi were also acceptable with rupture life and elongation. of 23.5 hr and 10.0%, respectively. The 1800°F rupture life, however, was only 0.5 hr above the 23-hr minimum requirement and represented a significant drop from the 44.5-hr rupture life of the baseline specimen with no prestrain or rejuvenation. The results of the 1400°F/85 ksi creep-rupture test showed a significant and unacceptable reduction in 1400°F creep properties with only 56.4 hr rupture life and 0.49% prior creep strain. The 0.49% prior creep strain was well below the PWA 658 required minimum of 2.0% and although the 56.4-hr rupture life was above the 23-hr requirement it was considered undesirable in view of a 764.2-hr life for nonrejuvenated IN 100 and a 333.7-hrCC life for CC IN 100 with one prestrain and rejuvenation heat treatment.

Based on the evaluations of the multiple rejuvenation testing for CC IN 100 it was concluded that the rejuvenation heat treatment of 2025°F/4 hr + 1600°F/12 hr effectively recovered CC IN 100 specimen properties after only one application of 1.0% creep strain at 1650°F/40 ksi. Subsequent prestrains and rejuvenations resulted in significant reductions of retest rupture and 1.0% creep life and in degradation of the creep curve behavior. In addition, the CC IN 100 1400°F creep-rupture properties were degraded beyond acceptability by the application of two prestrain/rejuvenation cycles.

The multiple rejuvenation test results also indicated that the use of a higher time or possibly temperature for each subsequent rejuvenation treatment may possibly improve the 1650°F creep property response of CC IN 100 to multiple rejuvenation. This area is recommended for additional investigation with strong emphasis on the ability of progressive time and/or temperature heat treatments to improve the 1400°F creep property response of CC IN 100 to multiple rejuvenation.

DS MAR-M200 + Hf Results

All prestrain and retest results for one, two, and three rejuvenations of DS MAR-M200 + Hf are tabulated in Table 12. It should be noted in Table 12 that five additional specimens, machined by conventional grinding, were given the double prestrain/rejuvenation cycle and retested to failure. These additional specimens were tested to increase the twice rejuvenated data base for DS MAR-M200 + Hf which was reduced to only two specimens because of a premature, shrink-initiated failure of one specimen during the second prestrain test. It should also be noted that the conventionally machined specimens exhibited slightly higher prestrain and rupture lives than the other specimens which were machined by electrochemical grinding. It is believed that these slightly higher properties were the result of initial heat treatment response in that any effects of machining, such as induced stresses, would have been eliminated by the first prestrain and subsequent rejuvenation heat treatment. As the conventionally ground specimens exhibited a similar response to multiple rejuvenation compared to the electrochemically ground specimens, the data was considered valid for incorporation.

The retest and total creep test results of Table 12 are compared in Figure 36 where it was clearly seen that the response of DS MAR-M200 + Hf specimens to multiple creep rejuvenation was much more favorable than that of CC IN 100. The average retest rupture lives and prior creep strains for the second and third prestrain/rejuvenation cycles were 128.2 hr and 12.0%, and 112.2 hr and 13.4%, respectively. Compared to the nonrejuvenated baseline rupture life of 125.2 hr, the double rejuvenated specimens exhibited 100% life recovery and the triple rejuvenated specimens exhibited 90% life recovery. However, compared to the single rejuvenation retest life of 145.2 hr, which comprises an effective 100% recovery plus an additional life improvement, the double and triple rejuvenated life recoveries are lowered to 88% and 77%, respectively. The latter comparison was considered the more valid of the two in assessing the actual rupture life recovery of DS MAR-M200 + Hf in that 100% recovery for the second and third rejuvenations should result in a rupture life equivalent to that following the first prestrain and rejuvenation heat treatment. The retest prior creep strains of the multiple rejuvenated specimens were still low in comparison to the average 16.4% prior creep of the baseline; however, they did remain in line with the 12.6% retest prior creep for one prestrain/rejuvenation cycle. This indicated that the lower creep strains of the rejuvenated specimens were inherent to the rejuvenation heat treatment and that the rejuvenation heat treatment successfully recovered the repeatedly induced creep strains.

The total (prestrain plus retest) creep properties of the multiple rejuvenated specimens were significantly increased over the baseline and single rejuvenation results because of the high degree of retest property recovery combined with the multiple prestrains. The specimens with two prestrain/rejuvenation cycles averaged a total rupture life and creep strain of 228.1 hr and 14.0%, while the triple rejuvenated specimens averaged 231.3 hr and 16.4%.

A comparison of the 1.0% creep life for nonrejuvenated and rejuvenated DS MAR-M200 + Hf specimens is presented in Figure 37. As with the previous 1.0% life comparison for CC IN 100, the nonrejuvenated 1.0% life average was determined from the initial 1.0% prestrains throughout the program, and the data base for the subsequent rejuvenated prestrains was increased by incorporating the applicable 1.0% creep lives from the rejuvenated retests. The 1.0% creep life behavior for the multiple rejuvenated DS MAR-M200 + Hf specimens closely paralleled that of the rejuvenated retest results. After one prestrain/rejuvenation cycle the average 1.0% creep life increased 20% for the nonrejuvenated baseline average of 40.1 hr to 48.0 hr. The second prestrain/rejuvenation cycle reduced the average 1.0% creep life to 39.4 hr, only 2% below baseline and essentially equivalent. The average 1.0% creep life after three prestrain rejuvenation cycles was 7% below the nonrejuvenated baseline at 37.4 hr.

TABLE 12. DS MAR-M200 + Hf CREEP TEST DATA FOR SPECIMENS WITH MULTIPLE 1.0% PRESTRAINS AND REJUVENATION HEAT TREATMENTS, 1800°F/28 ksi

Test Group Identification	Prestrain Test Time to 1.0% Strain: First 1.0%* (hr)	Second 1.0%* (hr)	Third 1.0% (hr)	Prestrain Test Totals: Time (hr)	Strain (%)	*Retest to Failure: Time to 1.0% Strain (hr)	Time to Rupture (hr)	Prior Creep Strain (%)	Prestrain and Retest Totals: Creep Strain (%)	Rupture Life (hr)	Rupture Elong (%)
One Rejuv Cycle	31.5	—	—	31.5	1.0	47.1	127.0	12.2	13.2	161.5	13.9
	32.4	—	—	32.4	1.0	49.8	151.6	15.2	16.2	184.9	19.5
	30.7	—	—	30.7	1.0	52.5	157.1	10.5	11.5	189.9	13.6
Average	31.5	—	—	31.5	1.0	49.8	145.2	12.6	13.6	178.8	15.7
Two Rejuv Cycles	46.4	34.8	—	81.2	2.0	30.0	114.5	19.0	21.0	195.7	21.6
	37.9	38.7	—	76.6	2.0	40.4	125.6	11.8	13.8	202.2	17.2
	**55.0	55.0	—	110.0	2.0	40.0	111.4	5.7	7.7	221.4	8.2
	**52.0	57.3	—	109.3	2.0	46.0	147.2	13.2	15.2	256.5	16.2
	**45.8	55.5	—	101.3	2.0	52.0	142.9	12.0	15.0	244.2	17.0
	**60.0	53.5	—	113.5	2.0	44.0	149.8	17.8	19.8	263.3	22.4
	**58.6	49.2	—	107.8	2.0	49.0	105.9	4.6	6.6	213.7	8.4
Average	50.8	49.1	—	99.9	2.0	43.1	128.2	12.0	14.0	228.1	15.9
Three Rejuv Cycles	37.4	42.6	29.5	109.5	3.0	41.4	125.2	14.9	17.9	234.7	23.9
	40.2	35.8	24.5	100.5	3.0	34.7	105.9	13.3	16.3	206.4	19.9
	56.2	51.9	39.0	147.4	3.0	36.2	105.5	12.0	15.0	252.9	22.5
Average	44.7	43.4	31.0	119.1	3.0	37.4	112.2	13.4	16.4	231.3	22.1

* Rejuvenated at 2200° F/10 hr + 1975°F/4 hr – 1600°F/32 hr — Fast Air Cool
** Specimens machined by conventional grindings

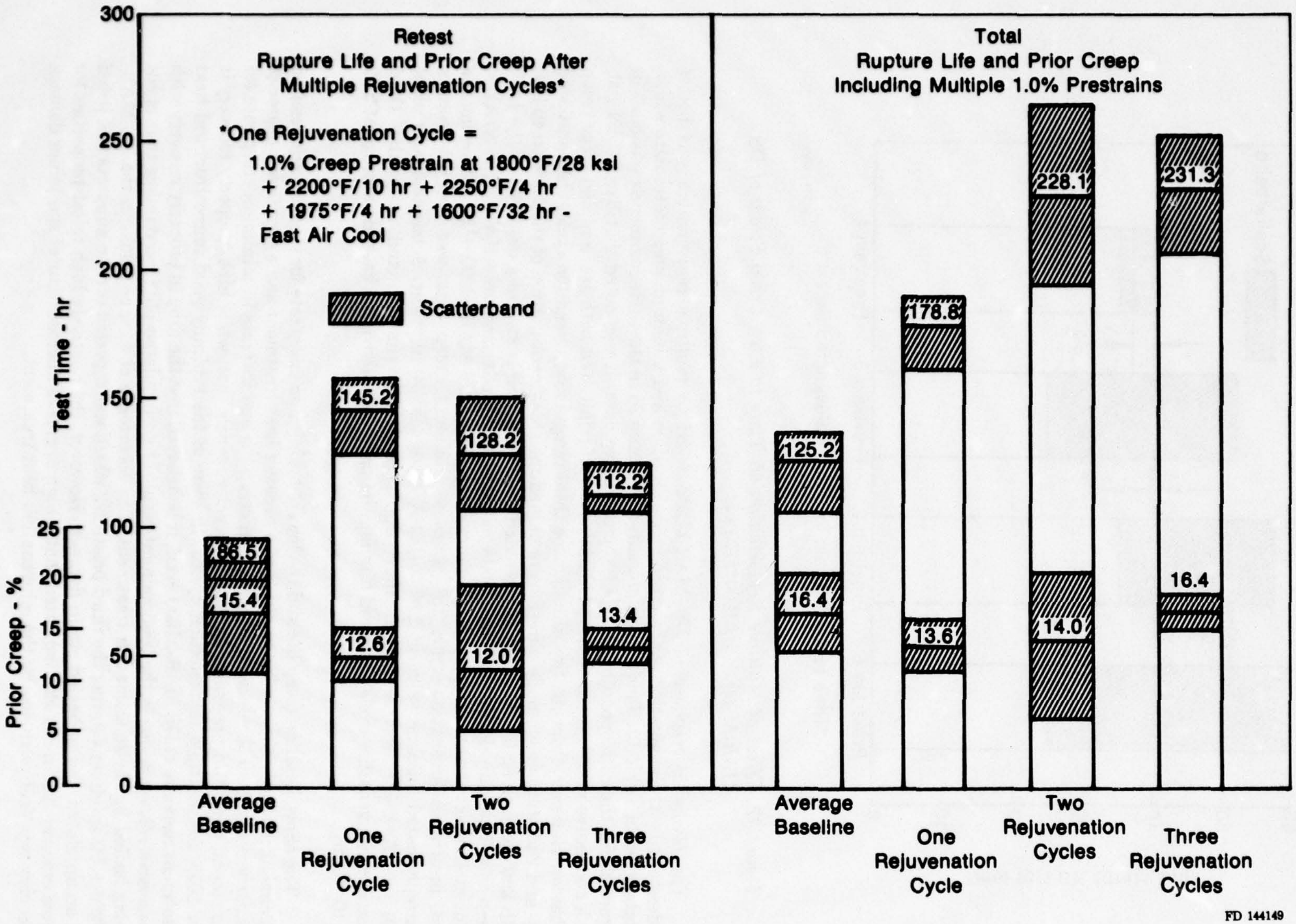


Figure 36. Effect of Multiple Rejuvenation on DS MAR-M200 + Hf Creep Properties, 1800°F/28 ksi

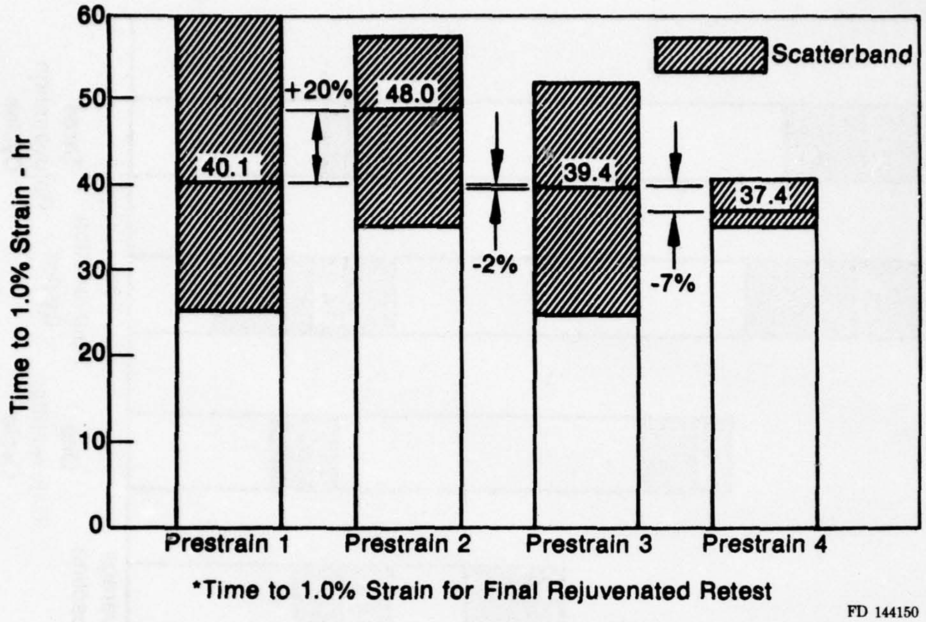


Figure 37. Effect of Multiple Rejuvenation on Time to 1.0% Creep Strain of DS MAR-M200 + Hf 1800°F/28 ksi

The favorable response of DS MAR-M200 + Hf to multiple rejuvenation was better understood by the evaluation of the creep mode duration and minimum creep rates data which is tabulated in Table 13. This data is presented in Figure 38 in the same manner as was done in Figure 35 for the corresponding CC IN 100 creep curve data. It was noted that like CC IN 100, each successive rejuvenation of DS MAR-M200 + Hf reinitiated both 1st- and 2nd-stage creep behavior. However, from the first through the third prestrain/rejuvenation cycle, the reinitiated 1st- and 2nd-stage creep mode durations remained the significant portion of the 1.0% creep life, with 2nd-stage creep for the triple rejuvenated specimens still comprising over 50% of the 1.0% creep life. The high degree of creep mode recovery was made more effective by the effect of rejuvenation heat treatment on the minimum creep rate of DS MAR-M200 + Hf. Following the first prestrain/rejuvenation cycle the average minimum creep rate was lowered from a nonrejuvenated baseline value of 2.02×10^{-2}%/hr to 1.88×10^{-2}%/hr. A baseline equivalent 2.01×10^{-2}%/hr was obtained after the second rejuvenation, and only the third prestrain/rejuvenation cycle produced a minimum creep rate above the baseline average at 2.12×10^{-2}%/hr.

The above baseline creep life and the lowered minimum creep rate for the once rejuvenated specimens is clearly the combined result of a superior heat treatment and a significant degree of property recovery. The successive decrease in creep life and increase in minimum creep rate for the second and third prestrain/rejuvenation cycles reveals that, while high, property recovery is not 100% for multiple rejuvenation cycles. In view of the typically good microstructural heat treatment response of DS MAR-M200 + Hf, it is believed that the drop in property recovery with successive rejuvenations is the predominant result of accumulated physical damage that is not being healed by the rejuvenation treatment. The occurrence of surface cracks in the DS MAR-M200 + Hf specimens during the third prestrain, which was reported earlier, supports this belief in accumulated and unhealed strain damage. However, the relatively high retest properties for these cracked specimens also indicated that a high degree of microstructural and minor damage recovery was still produced by the rejuvenation heat treatment.

TABLE 13. DS MAR-M200 + Hf CREEP CURVE DATA FOR BASELINE AND REJUVENATED SPECIMENS, 1800°F/28 ksi

Test Group Identification	*Initial 1.0% Prestrain* Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10⁻²)	*Second 1.0% Prestrain* Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10⁻²)	*Third 1.0% Prestrain* Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10⁻²)	*Third Rejuv Retest* Creep Stage Duration 1st (hr)	2nd (hr)	3rd (hr)	Min Creep Rate (%/hr×10⁻²)
Continuous Baseline	10	30	1	2.22												
	8	30	5	2.08												
	10	28	5	1.89												
	10	26	3	2.30												
One Rejuv Cycle	10	22	—	2.83	15	27	5	1.94								
	12	17	3	2.50	14	36	—	1.85								
	10	21	—	2.82	13	38	2	1.72								
Two Rejuv Cycles	7	35	4	2.06	10	21	2	2.50	8	22	—	2.66				
	10	28	—	1.99	8	31	—	2.34	7	23	10	2.16				
	14	41	—	1.49	6	30	19	1.35	9	27	4	1.55				
	20	32	—	1.62	6	32	19	1.48	8	26	12	1.62				
	12	24	10	1.64	6	28	22	1.[illegible]	8	32	12	1.44				
	16	38	6	1.44	4	36	14	1.59	7	30	7	1.66				
	9	41	9	1.57	5	24	20	1.53	8	27	14	1.46				
Three Rejuv Cycles	12	25	—	2.13	6	37	—	2.23	5	20	5	2.95	7	21	13	1.91
	10	22	8	2.12	8	26	2	2.60	6	14	5	3.41	3	17	15	2.32
	12	45	—	1.67	10	42	—	1.95	8	20	11	2.12	6	18	12	2.14
Average	11	30	3	2.02	9	31	8	1.88	7	24	8	2.01	5	19	13	2.12

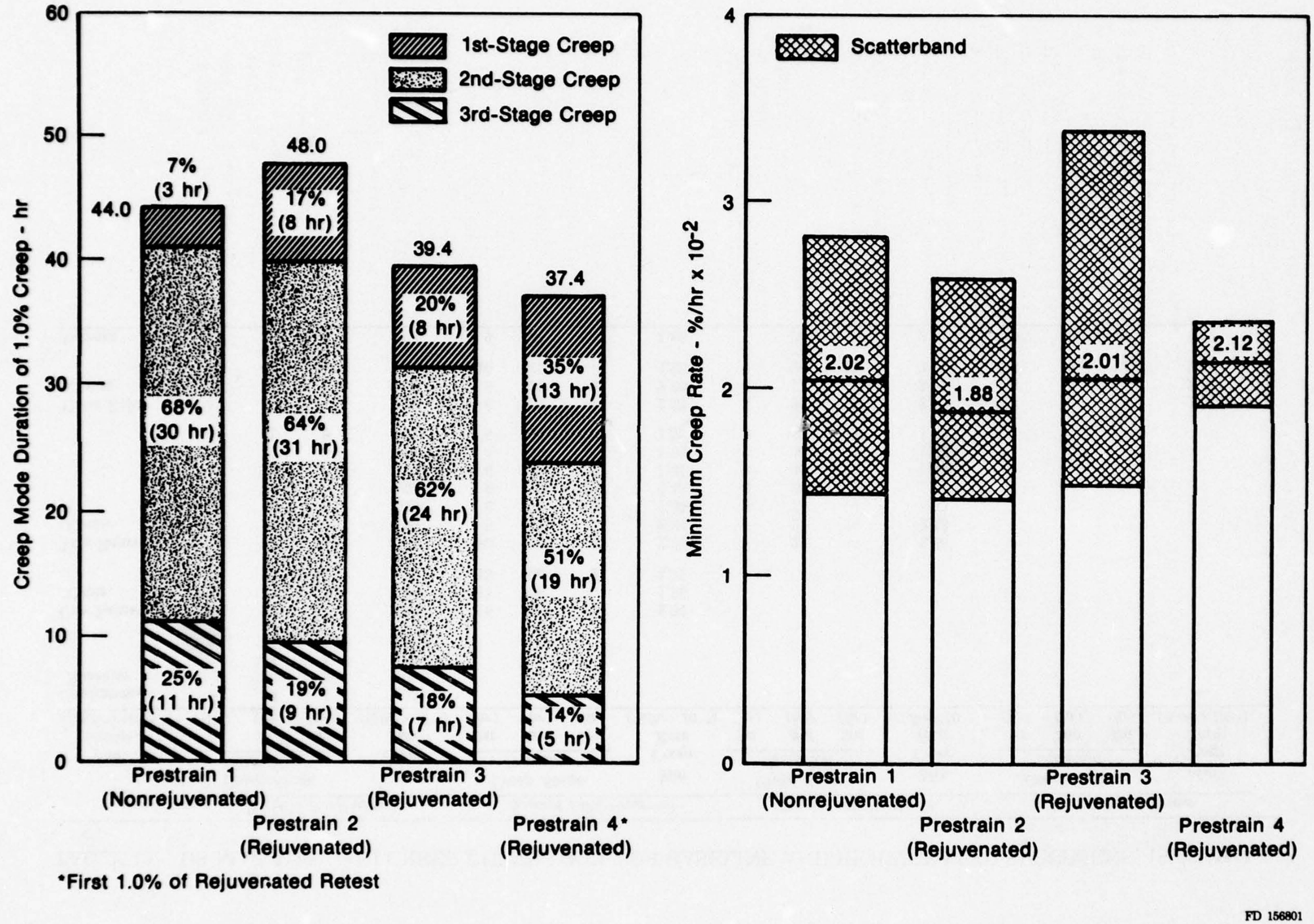


Figure 38. DS MAR-M200 + Hf 1.0% Creep Curve Data Comparison for Specimens With Multiple Rejuvenations, 1800°F/28 ksi

Based on the previous data observations and evaluations it is concluded that the rejuvenation heat treatment of 2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr with an equivalent fast air cool can repeatedly recover the 1800°F/28 ksi creep properties of DS MAR-M200 + Hf specimens for up to two applications of 1.0% strain at 1800°F/28 ksi.

Fatigue Rejuvenation

The previous test evaluations have dealt solely with the recovery of creep properties by thermal rejuvenation. In this test evaluation the effects of the rejuvenation heat treatments on strain controlled low-cycle fatigue, (LCF) and high-cycle fatigue, (HFC) properties was investigated.

The low- and high-cycle evaluation for CC IN 100 at 1650°F and for DS MAR-M200 + Hf at 1800°F consisted of baseline testing and rejuvenation testing. The baseline testing had two purposes: to select the strain or stress parameters for rejuvenation testing and to determine the number of cycles to which the specimens could be run without initiating irreversible damage. For CC IN 100, acoustic emission monitoring was performed during the baseline tests to determine the cyclic life for microcrack initiation. Acoustic emission did not produce interpretable signals for DS MAR-M200 + Hf and, therefore, an estimate of irreversible damage initiation for LCF was based on the number of cycles to a 5% stress range drop, which generally denotes a 0.030 through 0.050 in. macrocrack. The selection of the number of cycles for rejuvenation testing of DS MAR-M200 + Hf in HCF was based on past testing experience.

The rejuvenation testing for each alloy/fatigue combination consisted of two sets of partial life tests, each followed by inspection and rejuvenation heat treatment, and final testing to failure. Comparisons were then made between the final rejuvenated test life and the baseline life to determine the effects of rejuvenation heat treatment on fatigue properties.

Strain Controlled Low-Cycle Fatigue Testing

The LCF baseline testing data for CC IN 100 and DS MAR-M200 + Hf with the respective acoustic emission (AE) crack initiation cycles and the 5% stress range drop cycles are tabulated in Tables 14 and 15, respectively. Regression analysis was performed on this data to produce mean and 2σ minimum failue and crack curves which are presented in Figure 39 for CC IN 100 and Figure 40 for DS MAR-M200 + Hf.

A total strain range of 0.5%, producing a mean regression life of 8970 cycles, was selected as the strain parameter for CC IN 100 rejuvenation testing. For DS MAR-M200 + Hf rejuvenation testing a total strain range of 0.95% for a mean regression life of 3870 cycles was selected. The number of partial life cycles used for the rejuvenation testing of CC IN 100 and DS MAR-M200 + Hf were 3000 and 1800, respectively. These values were arbitrarily selected below the derived 2σ minimum values for crack occurrence at the selected strain ranges.

Following the first set of partial life testing for each alloy at the above selected strain and life parameters, 10× visual and fluorescent penetrant inspection was performed to assure that no surface damage had occurred. Upon inspection all CC IN 100 specimens were found to have significant visual surface cracks. All but one of the DS MAR-M200 + Hf specimens were also found to contain cracks. Examples of these surface cracks are shown for CC IN 100 in Figure 41 and for DS MAR-M200 + Hf in Figure 42.

TABLE 14. CC IN 100 STRAIN CONTROLLED LOW-CYCLE FATIGUE BASELINE TEST RESULTS, MEAN STRAIN = 0, FREQUENCY = 10 CPM, TEMPERATURE = 1650°F

Total Strain Range (%)	*Cycles To AE* Crack Initiation*	*Cycles To Failure*	*Remarks*
1.00	320	394	
0.80	760	1,116	
0.60	2,200	2,546	
0.60	1,900	2,750	
0.50	6,800	9,702	
0.50	4,500	6,299	
0.50	8,000	12,548	
0.50	5,300	10,563	
0.40	50,000	70,000	Did Not Fail

*Acoustic Emission

TABLE 15. DS MAR-M200 + Hf STRAIN CONTROLLED LOW-CYCLE FATIGUE BASELINE TEST RESULTS, MEAN STRAIN = 0, FREQUENCY = 10 CPM, TEMPERATURE = 1800°F

Total Strain Range (%)	**Cycles To 0.030 to 0.050 Inch Macro Crack*	*Cycles To Failure*
1.50	200	242
1.25	350	379
1.00	2,100	2,251
1.00	3,334	3,450
0.95	3,716	3,827
0.95	3,750	3,867
0.95	4,778	4,851
0.80	11,716	12,516
0.65	36,433	36,704

*Cycles to 5% Stress Range Drop

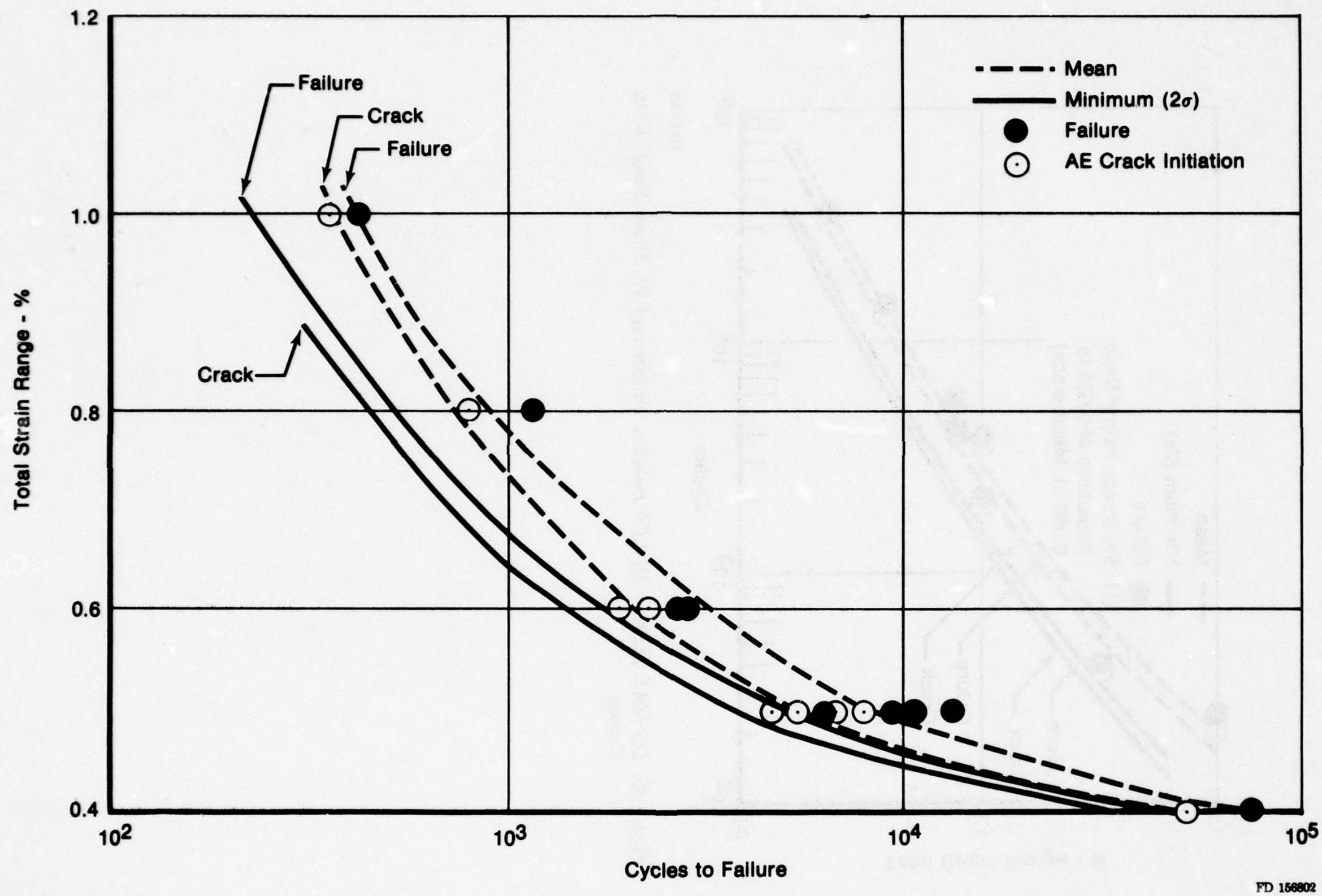


Figure 39. CC IN 100 LCF Baseline Failure and AE Crack Initiation Curves

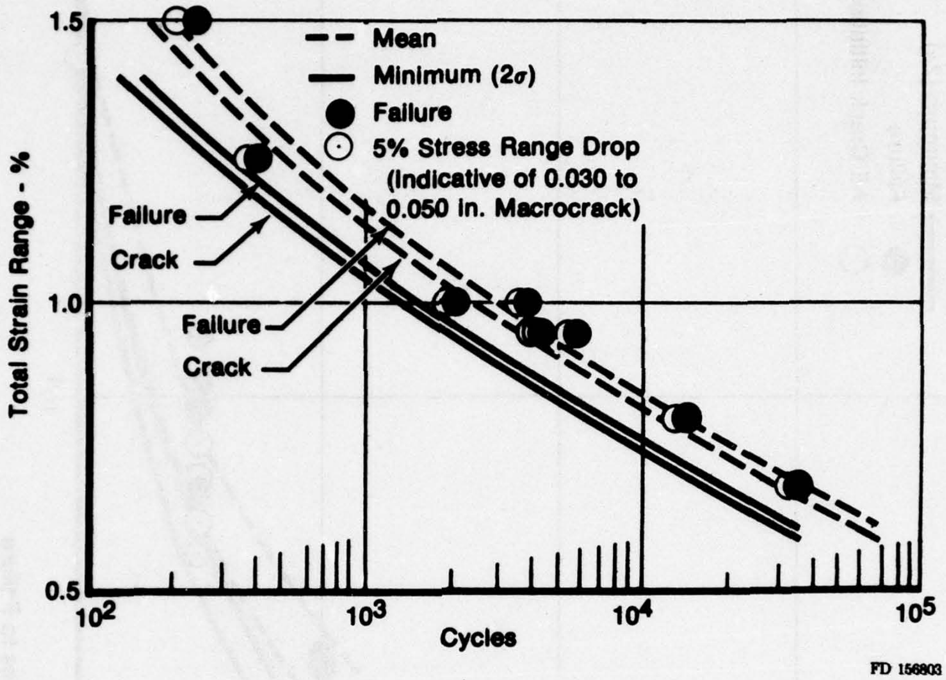


Figure 40. DS MAR-M200 + Hf LCF Baseline Failure and 5% Stress Range Drop Curves

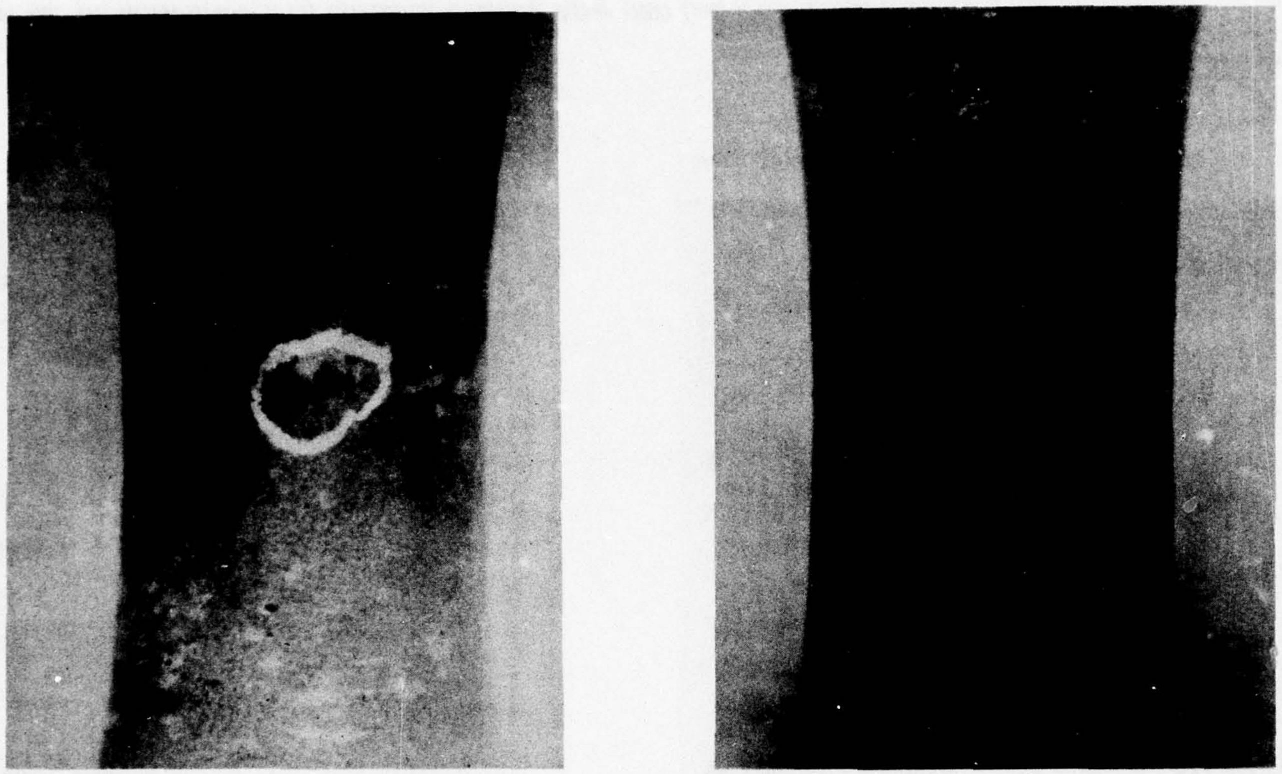


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Figure 41. CC IN 100 Specimen Cracking After 3000 Low-Cycle Fatigue Cycles

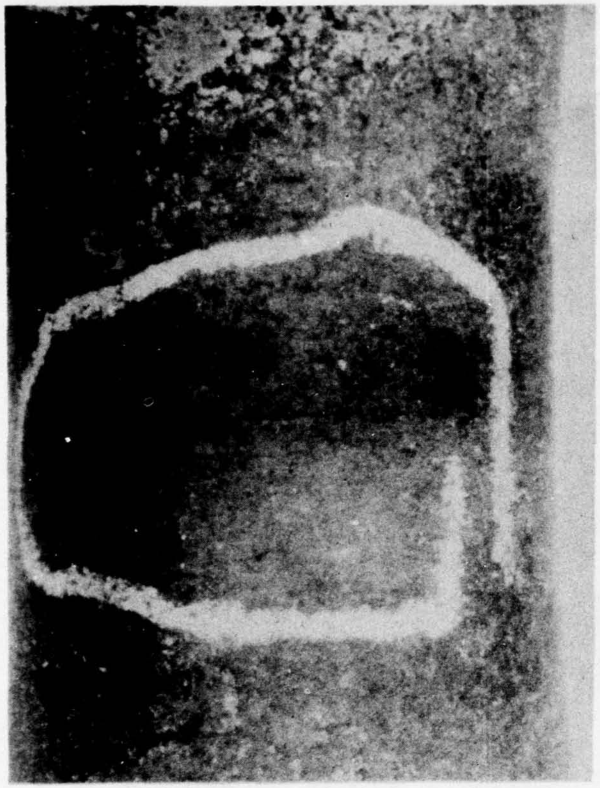

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Figure 42. DS MAR-M200 + Hf Specimen Cracking After 1800 Low-Cycle Fatigue Cycles

Reduction of the specimen gage diameter was investigated as a means of continuing the test evaluation; however, this was prohibited because of extremely tight diameter and radius limits required for the specimen in order to maintain a representative strain controlled test. The LCF test evaluations for both CC IN 100 and DS MAR-M200 + Hf were therefore terminated in view of the fact that a subsequent evaluation remained to be performed on the effects of rejuvenation on combined LCF/creep properties.

Axial High-Cycle Fatigue Testing

The HCF baseline testing data is tabulated in Tables 16 and 17, and regression mean and 2σ minimum curves are plotted in Figures 43 and 44 for CC IN 100 and DS MAR-M200 + Hf, respectively. For CC IN 100 an alternating cyclic stress of 35 ksi was selected for use in the rejuvenation testing. This stress level produced a mean regression life of 1.4×10^6 cycles and a minimum AE crack initiation of 1.0×10^6 cycles. A selection of 1.0×10^6 cycles was risked for the partial life testing limit in that it was desirable to accumulate as many rejuvenation cycles as possible in two sets of testing to improve the possibility of proving HCF life recovery.

The stress level selected for rejuvenation testing of DS MAR-M200 + Hf was 45 ksi, which produced a mean regression life of 7.50×10^6 cycles. A maximum, safe partial life limit was estimated at 1.5×10^6 cycles based on DS MAR-M200 + Hf HCF testing experience.

The partial life testing, inspection, and rejuvenation heat treatments for CC IN 100 proceeded without mishaps for the CC IN 100 specimens. Following each of the two partial life tests to 1.0×10^6, inspection revealed no evidence of gage surface damage. For DS MAR-M200 + Hf, however, one specimen failed prematurely at 5.4×10^4 cycles during the first sequence of testing. This was believed to be the result of an internal dross inclusion; however, the test machine did not have automatic cut-off capability and the fracture face was damaged beyond the limits for investigation. During the second sequence of partial life testing a second DS MAR-M200 + Hf specimen was prematurely failed because of machine misalignment. Excluding these two mishaps, no additional problems were encountered in the rejuvenation testing of DS MAR-M200 + Hf.

Prior to initiating the HCF failure testing following the second rejuvenation heat treatment, the 90% confidence level boundaries for HCF life recovery and degradation were determined from the existing test data for both alloys. This was primarily done to provide an arbitrary test discontinuation life because of the long time and expense involved in testing to a high number of cycles. For CC IN 100, 90% confidence of life recovery/improvement would be assured by a retest average exceeding 2.36×10^6 cycles, while a retest average below 8.3×10^5 cycles would denote 90% confidence of HCF life degradation by the rejuvenation heat treatment. The similar 90% confidence limits for DS MAR-M200 + Hf were 1.34×10^6 cycles for life recovery/improvement and 4.15×10^5 cycles for life degradation. Instructions were given for the failure testing that tests continuing beyond these upper limits for each alloy could be discontinued at the discretion of the test engineer.

The HCF retest failure data is tabulated in Tables 18 and 19 and plotted against the baseline testing failure curves in Figures 45 and 46 for CC IN 100 and DS MAR-M200 + Hf, respectively. All of the CC IN 100 tests ran beyond the upper 90% confidence level and were discontinued at various life levels from 2.92×10^6 cycles to 1.0×10^7 cycles, resulting in a discontinued life average of 4.94×10^6 cycles. It can therefore be concluded with 90% confidence the the CC IN 100 rejuvenation heat treatment recovered and/or improved the HCF life of the specimens tested at 1650°F and 35 ksi alternating stress.

TABLE 16. CC IN 100 AXIAL HIGH-CYCLE FATIGUE BASELINE TEST RESULTS MEAN STRESS = 0, FREQUENCY = 30 Hz, K_t = 1, TEMPERATURE = 1650°F

Alternating Stress (±ksi)	*Cycles To AE * Crack Initiation*	*Cycles To Failure*	*Remarks*
60		1.54×10^4	
50	4.21×10^4	6.38×10^4	
45	2.07×10^5	2.59×10^5	
40	3.32×10^5	4.00×10^5	
30		2.22×10^6	
30		7.34×10^6	
35			Machine Malfunction, Specimen Tensiled
35		2.4×10^6	
35	3.1×10^6	3.3×10^6	

*Acoustic Emission

TABLE 17. DS MAR-M200 + Hf AXIAL HIGH-CYCLE FATIGUE BASELINE TEST RESULTS, MEAN STRESS = 0, FREQUENCY = 30Hz, K_t = 1, TEMPERATURE = 1800°F

Alternating Stress (±ksi)	*Cycles To Failure*	*Remarks*
60	8.09×10^4	
55	2.29×10^5	
50	4.62×10^5	
45	2.55×10^5	
40	10^7	Did Not Fail
45	3.50×10^5	
45	9.10×10^5	
45	2.70×10^4	Internal Defect - Hf Dross
45	6.73×10^5	

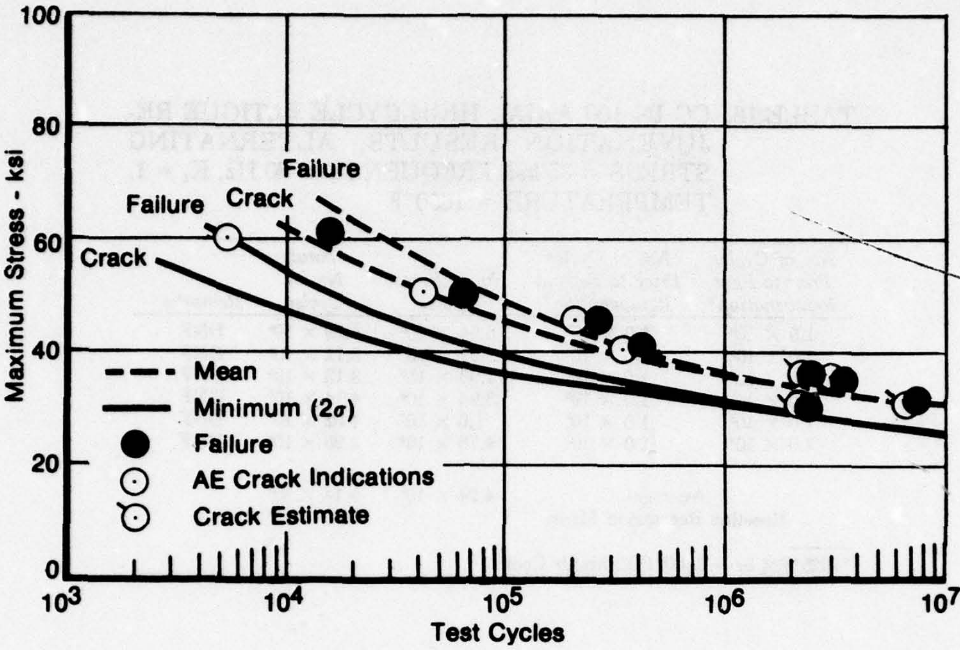

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Figure 43. CC IN 100 HCF Baseline and AE Crack Initiation Curves

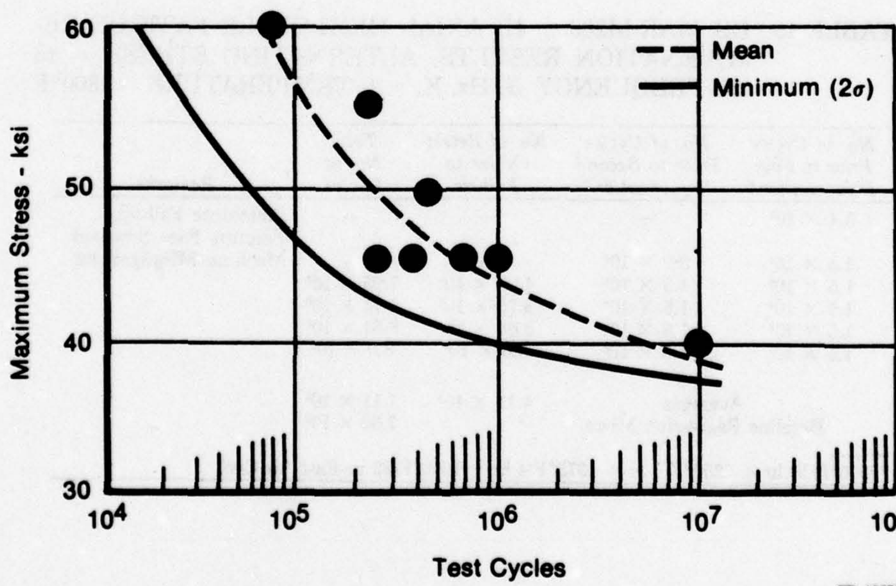

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Figure 44. DS MAR-M200 + Hf High-Cycle Fatigue Baseline Failure Curve

TABLE 18. CC IN 100 AXIAL HIGH-CYCLE FATIGUE REJUVENATION RESULTS, ALTERNATING STRESS = 35 ksi, FREQUENCY = 30 Hz, K_t = 1, TEMPERATURE = 1650°F

*No. of Cycles Prior to First Rejuvenation**	*No. of Cycles Prior to Second Rejuvenation**	*No. of Retest Cycles*	*Total No. of Cycles*	*Remarks*
1.5×10^5	1.0×10^5	5.04×10^6	5.29×10^6	DNF
1.0×10^5	1.0×10^5	2.92×10^6	3.12×10^6	DNF
1.0×10^5	1.0×10^5	2.93×10^6	3.13×10^6	DNF
1.0×10^5	1.0×10^5	3.94×10^6	4.14×10^6	DNF
1.0×10^5	1.0×10^5	1.0×10^7	1.02×10^7	DNF
1.0×10^5	1.0×10^5	4.78×10^6	4.98×10^6	DNF
	Averages	4.94×10^6	5.14×10^6	
	Baseline Regression Mean		1.40×10^6	

*2025°F/4 hr + 1600°F/12 hr-Air Cool

TABLE 19. DS MAR-M200 + Hf AXIAL HIGH-CYCLE FATIGUE REJUVENATION RESULTS, ALTERNATING STRESS = 45 ksi, FREQUENCY 30 Hz, K_t = 1, TEMPERATURE = 1800°F

*No. of Cycles Prior to First Rejuvenation**	*No. of Cycles Prior to Second Rejuvenation**	*No. of Retest Cycles to Failure*	*Total No. of Cycles*	*Remarks*
5.4×10^4	—	—	—	Premature Failure, Fracture Face Smeared
1.5×10^5	3.2×10^4	—	—	Machine Misalignment
1.5×10^5	1.5×10^5	4.05×10^5	7.05×10^5	
1.5×10^5	1.5×10^5	3.75×10^5	6.75×10^5	
1.5×10^5	1.5×10^5	3.64×10^5	6.64×10^5	
1.5×10^5	1.5×10^5	5.0×10^5	8.0×10^5	
	Averages	4.11×10^5	7.11×10^5	
	Baseline Regression Mean		7.30×10^5	

*2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr-Fast Air Cool

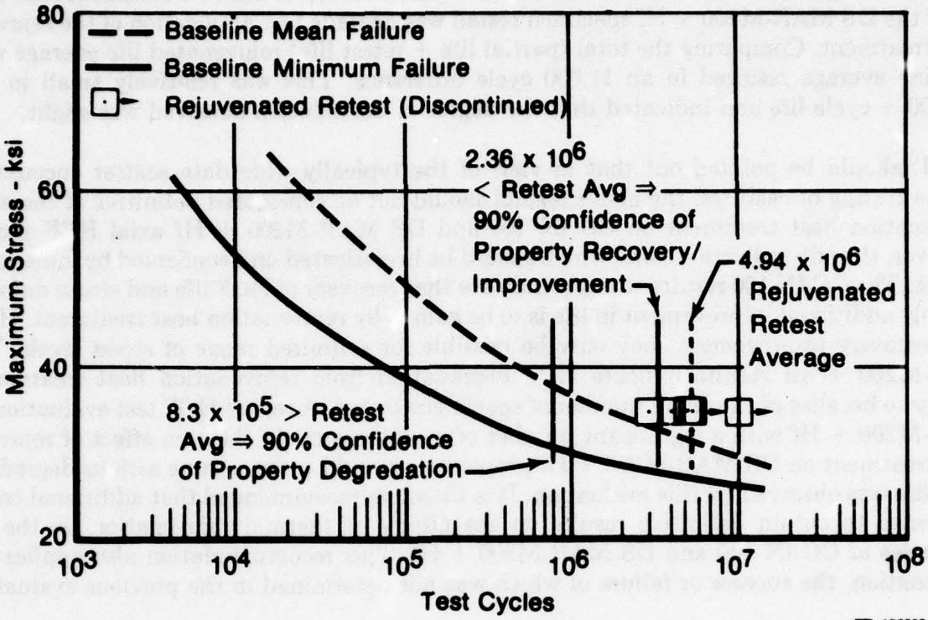

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Figure 45. CC IN 100 High-Cycle Fatigue Property Comparison Between Rejuvenated and Nonrejuvenated Material

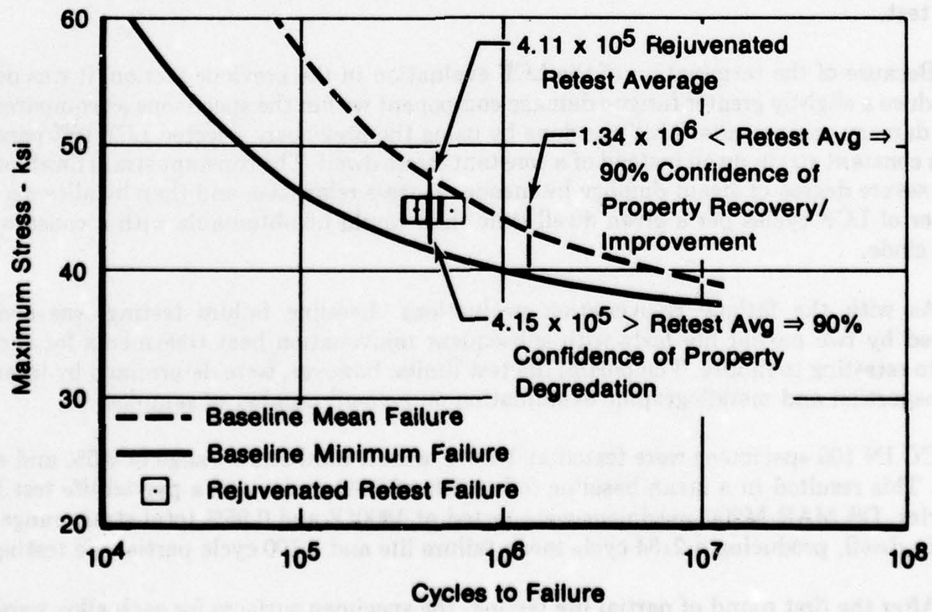

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Figure 46. DS MAR-M200 + Hf High-Cycle Fatigue Property Comparison Between Rejuvenated and Nonrejuvenated Material

The DS MAR-M200 + Hf specimens failed before reaching the baseline mean failure life with an average life of 4.11 × 10^5 cycles. Based on these results it was 90% confident that the HCF life of the DS MAR-M200 + Hf specimen tested was degraded by application of the rejuvenation heat treatment. Comparing the total (partial life + retest life) rejuvenated life average with the baseline average resulted in an 11,000 cycle difference. This was relatively small in view of 700,000 + cycle life and indicated that the degree of degradation observed was slight.

It should be pointed out that in view of the typically wide data scatter encountered in fatigue testing of castings, the above results should not be considered definitive of the effects of rejuvenation heat treatment on CC IN 100 and DS MAR-M200 + Hf axial HCF properties. However, they do indicate a trend which should be investigated and confirmed by more extensive testing. The CC IN 100 results strongly indicate that recovery of HCF life and strain damage and possibly additional improvement in life is to be gained by rejuvenation heat treatment. However, such recovery improvement may only be possible for a limited range of stress levels. The DS MAR-M200 + Hf results indicate HCF degradation from rejuvenation heat treatment, but weakly so because of the small number of specimens tested. A repeat HCF test evaluation for DS MAR-M200 + Hf with a significant number of specimens could show no effect of rejuvenation heat treatment on DS MAR-M200 + Hf properties or could prove a more serious degradation of HCF life was observed by this evaluation. It is therefore recommended that additional testing be performed to obtain definitive results on the effects of thermal rejuvenation on the fatigue properties of CC IN 100 and DS MAR-M200 + Hf. This recommendation also applies to LCF rejuvenation, the success or failure of which was not determined in the previous evaluation.

Cumulative Creep/Fatigue Rejuvenation

As the strain damage experienced by a turbine blade in service is a combination of both creep and fatigue damage, it was desirable to investigate the effects of thermal rejuvenation on CC IN 100 and DS MAR-M200 + Hf specimens with combined creep and fatigue damage. This was done using LCF/dwell testing to accumulate both LCF damage and creep damage within the same test.

Because of the termination of the LCF evaluation in the previous section, it was desirable to produce a slightly greater fatigue damage component within the specimens as compared to the creep damage components. This was done by using the previously selected LCF test parameters with a constant strain dwell instead of a constant stress dwell. The constant strain dwell produces a less severe degree of strain damage by means of stress relaxation and thereby allows a greater number of LCF cycles per a given dwell time than would be obtainable with a constant stress dwell mode.

As with the fatigue rejuvenation evaluations, baseline failure testing was conducted followed by two partial life tests with subsequent rejuvenation heat treatments for each alloy prior to retesting to failure. The partial life test limits, however, were determined by interrupted test inspection and metallographic examination on a small number of samples.

CC IN 100 specimens were tested at 1650°F with a total strain range of 0.5% and a 2 min dwell. This resulted in a mean baseline failure life of 3450 cycles and a partial life test limit of 50 cycles. DS MAR-M200 specimens were tested at 1800°F and 0.95% total strain range with a 0.5 min dwell, producing a 2134 cycle mean failure life and a 100 cycle partial life testing limit.

After the first round of partial life testing, the specimen surfaces for each alloy were free of any damage indications. However, after the second round of prestrain tests, two of the CC IN 100 specimens exhibited the surface cracks illustrated in Figure 47. Irregardless of the surface cracking the specimens were rejuvenation heat-treated and tested to failure. The DS MAR-M200 + Hf specimens exhibited no surface damage after the second round of testing and were subsequently rejuvenated and retested to failure.

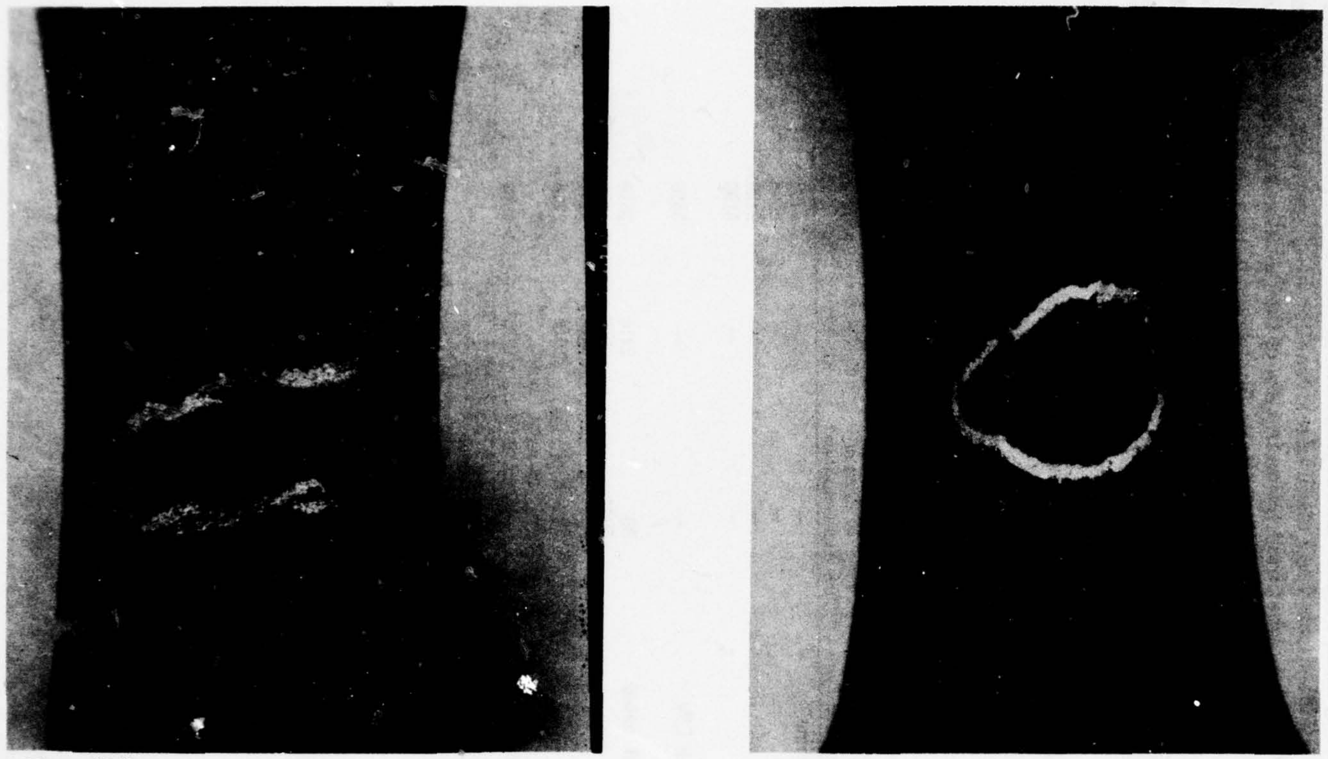

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Figure 47. CC IN 100 Gage Surface Cracks After 100 LCF/Dwell Cycles Prior to Final Rejuvenation Treatment

Tables 20 and 21 list both the baseline failure and the rejuvenation retest results for CC IN 100 and DS MAR-M200 + Hf, respectively. Mean and a 2σ minimum comparison between the baseline cycles to failure and the total cycles to failure for rejuvenated specimens were presented for both alloys in Figure 48.

Based on the existing data, a significant degradation in LCF/dwell properties for CC IN 100 and DS MAR-M200 + Hf is indicated as a result of rejuvenation heat treatment. The degradation indicated for CC IN 100 is somewhat in question in view of the fact that two of four rejuvenated specimens contained existing surface cracks prior to final rejuvenation and retesting to failure. However, one of these two specimens had the highest life which supported their inclusion of both specimens with the other data. The degradation of DS MAR-M200 + Hf specimens is strongly supported by eight rejuvenation tests. The mean failure for the rejuvenated specimens was 970 cycles as compared to the baseline mean failure of 2134 cycles.

TABLE 20. CC IN 100 LOW-CYCLE FATIGUE/DWELL TEST RESULTS, TOTAL STRAIN RANGE = 0.5% MEAN STRAIN = 0, DWELL TIME = 2 MINUTES ϵ_{max}, TEMPERATURE = 1650°F

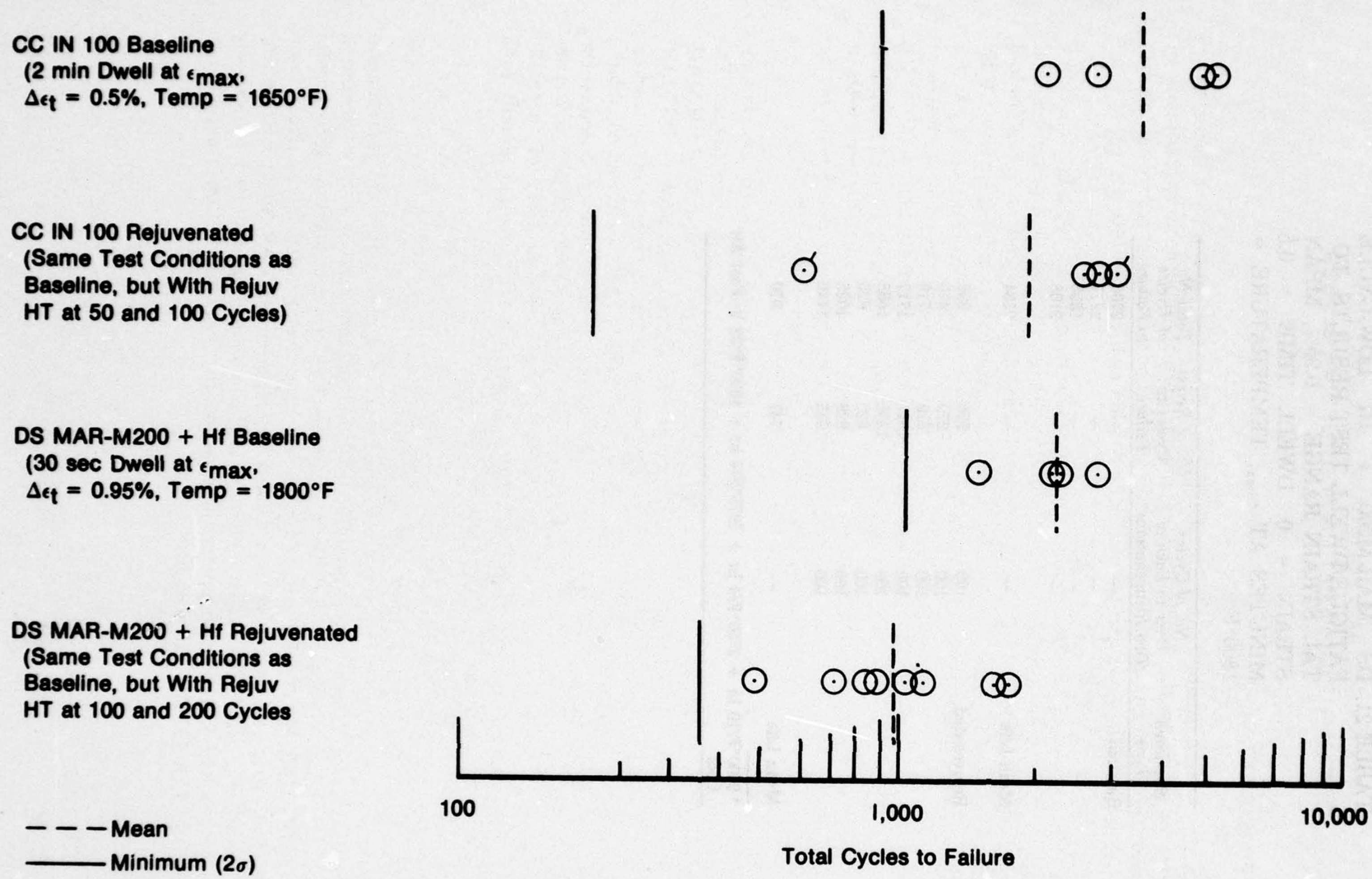
Specimen Type	*No. of Cycles Prior to Each of Two Rejuvenations**	*No. of Retest Cycles to Failure*	*Total No. of Cycles to Failure*
Baseline	—	—	4793
	—	—	2686
	—	—	2120
	—	—	5190
Mean Life	—	—	3450
Rejuvenated	50	2416	2516
	50**	509	609
	50**	2839	2939
	50	2618	2718
Mean Life	—	1739	1870

* 2025°F/4 hr + 1600°F/12 hr-Air Cool
** Gage surface crack observed after 100 cycles prior to final rejuvenation

TABLE 21. DS MAR-M200 + Hf LOW-CYCLE FATIGUE/DWELL TEST RESULTS, TOTAL STRAIN RANGE = 0.95%, MEAN STRAIN = 0, DWELL TIME = 0.5 MINUTES AT ϵ_{max}, TEMPERATURE = 1800°F

Specimen Type	No. of Cycles Prior to Each of Two Rejuvenations*	No. of Retest Cycles to Failure	Total No. of Cycles to Failure
Baseline	—	—	2706
	—	—	2277
	—	—	1598
	—	—	2108
Mean Life	—	—	2134
Rejuvenated	100	695	895
	100	270	470
	100	519	719
	100	1517	1717
	100	1358	1558
	100	620	820
	100	828	1028
	100	945	1145
Mean Life	—	747	970

* 2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr-Fast Air Cool



Flagged Symbol Denotes Gage Surface Crack After 1000 Cycles Prior to Final Rejuvenation Heat Treatment

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Figure 48. CC IN 100 and DS MAR-M200 + Hf Comparisons of LCF/Dwell Properties for Specimens With and Without Rejuvenation Heat Treatment

SECTION IV

TECHNICAL AND ECONOMIC FEASIBILITY OF THERMAL REJUVENATION FOR TURBINE BLADES

TECHNICAL FEASIBILITY

As this program was a feasibility investigation performed on test bars and not blades, there were limitations in assessing the feasibility of applying thermal rejuvenation treatments to turbine blades for the purpose of extending useful blade life. These limitations involved test bar vs blade microstructure differences and thermal rejuvenation response limitations.

Blade vs test bar microstructure differences apply primarily to CC IN 100 alloy. This alloy is casting process sensitive or, in other words, the microstructure, mechanical properties, and slight response to heat treatment of CC IN 100 components are highly dependent on and limited by the casting process used to produce them. Because of this initial processing sensitivity, CC IN 100 turbine blade microstructures and properties are not the same as those for CC IN 100 test bars. Hence, the observed effects on CC IN 100 test bars of the rejuvenation heat treatment evaluated in this program may not be of the same degree or nature when applied to CC IN 100 turbine blades. Also, CC IN 100 blades may require a significantly different thermal treatment from that evaluated to exhibit any degree of property recovery at all. Therefore without microstructural and test evaluations on actual hardware, an accurate assessment of the feasibility of thermal rejuvenation of CC IN 100 turbine blades cannot be made.

Blade vs test bar microstructure differences for DS MAR-M200 + Hf have little effect on the application of thermal rejuvenation treatments to DS MAR-M200 + Hf turbine blades. The controlled solidification of the DS process and the good heat treatment response of DS MAR-M200 + Hf tend to produce little difference in microstructure and properties between DS MAR-M200 + Hf test bars and turbine blades. Therefore, application to turbine blades of the thermal rejuvenation treatment evaluated in this program for DS MAR-M200 + Hf was considered technically feasible for the purpose of increasing useful blade creep life. However, based on the results of this program the response to rejuvenation of DS MAR-M200 + Hf fatigue properties was undesirable at worst to questionable at best. Therefore, the feasibility of thermally rejuvenating DS MAR-M200 + Hf turbine blades must, at this time, be qualified to only such blades as have no primary or secondary limitations in fatigue.

ECONOMIC FEASIBILITY

An accurate assessment of the economic feasibility of applying thermal rejuvenation treatments to CC IN 100 turbine blades cannot be made for the same reasons as those presented for technical feasibility. However, significant cost savings appear possible for thermal rejuvenation of DS MAR-M200 + Hf turbine blades that have creep limited service lives. Based on the results of this program, thermal rejuvenation of creep limited DS MAR-M200 + Hf turbine blades could result in doubling the current creep limits of the blades. Incorporated into existing tip repair procedures with full blade stripping and recoating, thermal rejuvenation is an economic feasibility for DS MAR-M200 + Hf blades.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

1. The optimum rejuvenation heat treatment for the recovery of Conventionally Cast (CC) IN 100 creep properties at 1650°F/40 ksi was 2025°F/4 hr + 1600°F/16 hr — air cool.

2. The optimum rejuvenation heat treatment for the recovery of DS MAR-M200 + Hf creep properties at 1800°F/28 ksi was 2200°F/10 hr + 2250°F/4 hr + 1975°F/4 hr + 1600°F/32 hr — fast air cool.

3. The maximum recoverable creep strain for the CC IN 100 rejuvenation treatment was 1.0% strain at 1650°F/40 ksi.

4. The maximum recoverable creep strain for the DS MAR-M200 + Hf rejuvenation treatment was 1.0% strain at 1800°F/28 ksi.

5. Application of 1.0% creep strain to CC IN 100 followed by rejuvenation heat treatment significantly degraded 1400°F creep properties, lowered 1800°F/28 si ruptured life, but had no significant effect on 70°F tensile properties.

6. Application of 1.0% creep strain to DS MAR-M200 + Hf followed by rejuvenation heat treatment show no significant effects on 1400°F creep, 1800°F/32 ksi stress rupture, or 70°F tensile properties.

7. The CC IN 100 rejuvenation treatment was capable of recovering baseline equivalent 1650°F/40 ksi creep properties for only one application of 1.0% creep strain.

8. The DS MAR-M200 + Hf rejuvenation treatment improved 1800°F/28 ksi creep properties after one application of 1.0% creep strain and maintained baseline equivalent properties after a second application of 1.0% creep strain.

9. The HCF properties of CC IN 100 were recovered and possibly improved by rejuvenation heat treatment.

10. Rejuvenation heat treatment slightly degraded HCF properties of DS MAR-M200 + Hf.

11. A decrease in LCF/dwell properties for CC IN 100 was indicated as a result of rejuvenation heat treatment.

12. The LCF/dwell properties of DS MAR-M200 + Hf were significantly degraded by application of the rejuvenation heat treatment.

RECOMMENDATIONS

Various degrees of property recovery improvement, and reduction have been observed for CC IN 100 and DS MAR-M200 + Hf as a result of thermal rejuvenation treatments on partially strain damaged specimens. However, no understanding has been developed of the controlling strain, thermal, and microstructural mechanisms of the rejuvenation process. To enable directed improvement of thermal rejuvenation processes a program should be initiated to identify the controlling mechanisms of rejuvenation and to define their range of influence.

A program for a definitive evaluation of the effects of rejuvenation heat treatment on fatigue properties of turbine blade materials should be initiated. Such a program should incorporate a sufficient number of tests to account for the high data scatter typical in cyclic testing of castings.

APPENDIX A
TEST SPECIMEN PROCUREMENT, INSPECTION, MACHINING, AND QUALIFICATION TESTING

CAST TEST BAR PROCUREMENT

Conventionally cast (CC) IN 100 and directionally solidified (DS) MAR-M200 + Hf test bars were purchased from the Misco Division of the Howmet Corp and Sherwood Metal Products Inc., respectively. Both foundries are current sources for F100 turbine blades cast in these alloys and, therefore, have the experience and expertise required to produce sound test bars.

The master heat used to produce CC IN 100 specimens was coded Ru-362. The chemical analysis of this master heat is presented in Table 22 along with chemistry limits of the PWA 658 specification. The master heat used for DS MAR-M200 + Hf specimens was one having a chemistry representative of desirable higher carbon and lower hafnium levels. The chemistry of this master heat, coded S-718, and the current PWA 1422 specification requirements are given in Table 23.

The CC IN 100 bars were cast in two configurations as shown in Figures 49 and 50. The first was the hourglass test bar which was be used for creep, tensile and high-cycle fatigue tests. The cast-to-size LCF bar, shown in Figure 50, was used for both low-cycle fatigue and combined creep/fatigue testing.

DS MAR-M200 + Hf test bars were supplied in the form of par bars as shown in Figure 51. All required test specimens were machined from this configuration.

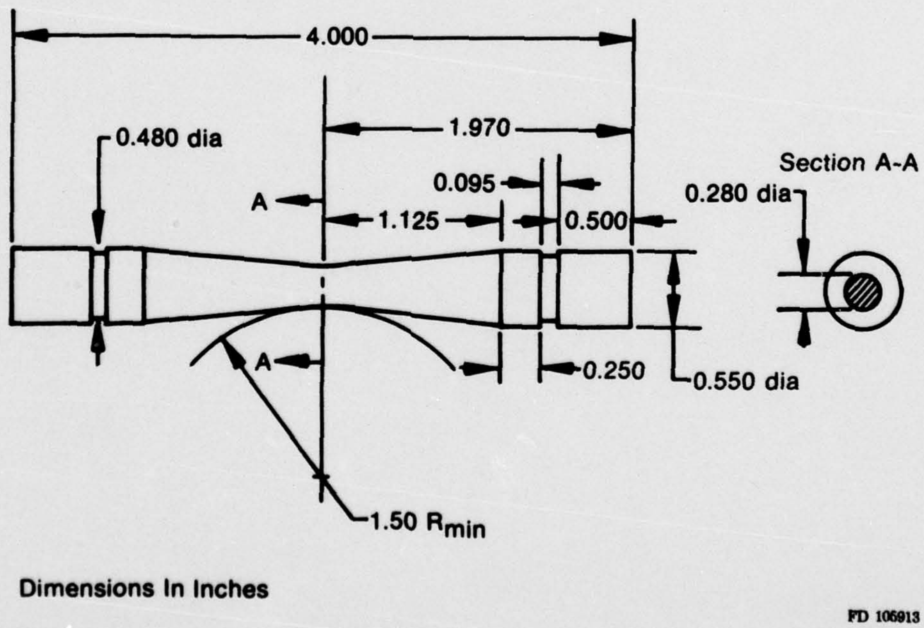


Figure 49. IN 100 Cast Hourglass Test Bar

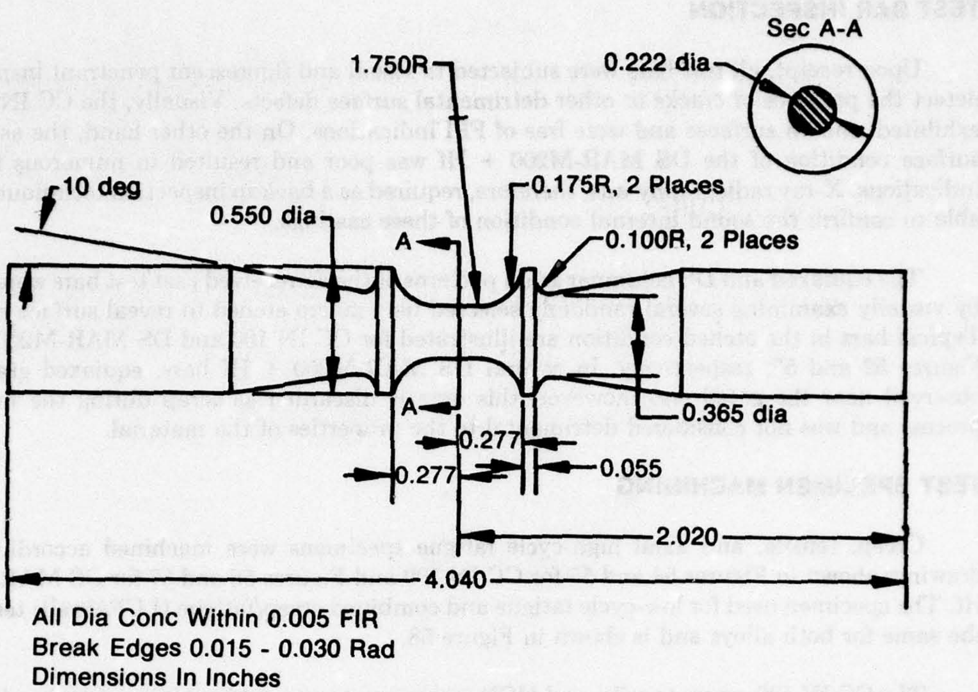


Figure 50. IN 100 Cast-to-Size LCF Specimen Prior to Machining

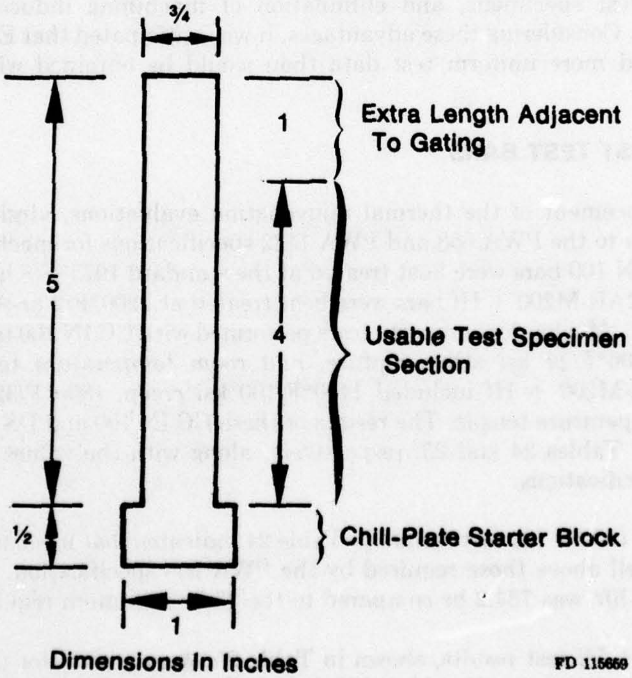


Figure 51. DS MAR-M200 + Hf Par Bar

TEST BAR INSPECTION

Upon receipt, all test bars were subjected to visual and fluorescent penetrant inspection to detect the presence of cracks or other detrimental surface defects. Visually, the CC IN 100 bars exhibited smooth surfaces and were free of FPI indications. On the other hand, the as-received surface condition of the DS MAR-M200 + Hf was poor and resulted in numerous false FPI indications. X-ray radiography was, therefore, required as a backup inspection technique and was able to confirm the sound internal condition of these castings.

The equiaxed and DS columnar grain patterns of the as-received cast test bars were checked by visually examining several randomly selected bars macro etched to reveal surface structure. Typical bars in the etched condition are illustrated for CC IN 100 and DS MAR-M200 + Hf in Figures 52 and 53, respectively. In several DS MAR-M200 + Hf bars, equiaxed grains were observed near the gated end; however, this area is discarded as scrap during the machining process and was not considered detrimental to the properties of the material.

TEST SPECIMEN MACHINING

Creep, tensile, and axial high-cycle fatigue specimens were machined according to the drawings shown in Figures 54 and 55 for CC IN 100 and Figures 56 and 57 for DS MAR-M200 + Hf. The specimen used for low-cycle fatigue and combined creep/fatigue (LCF/dwell) testing was the same for both alloys and is shown in Figure 58.

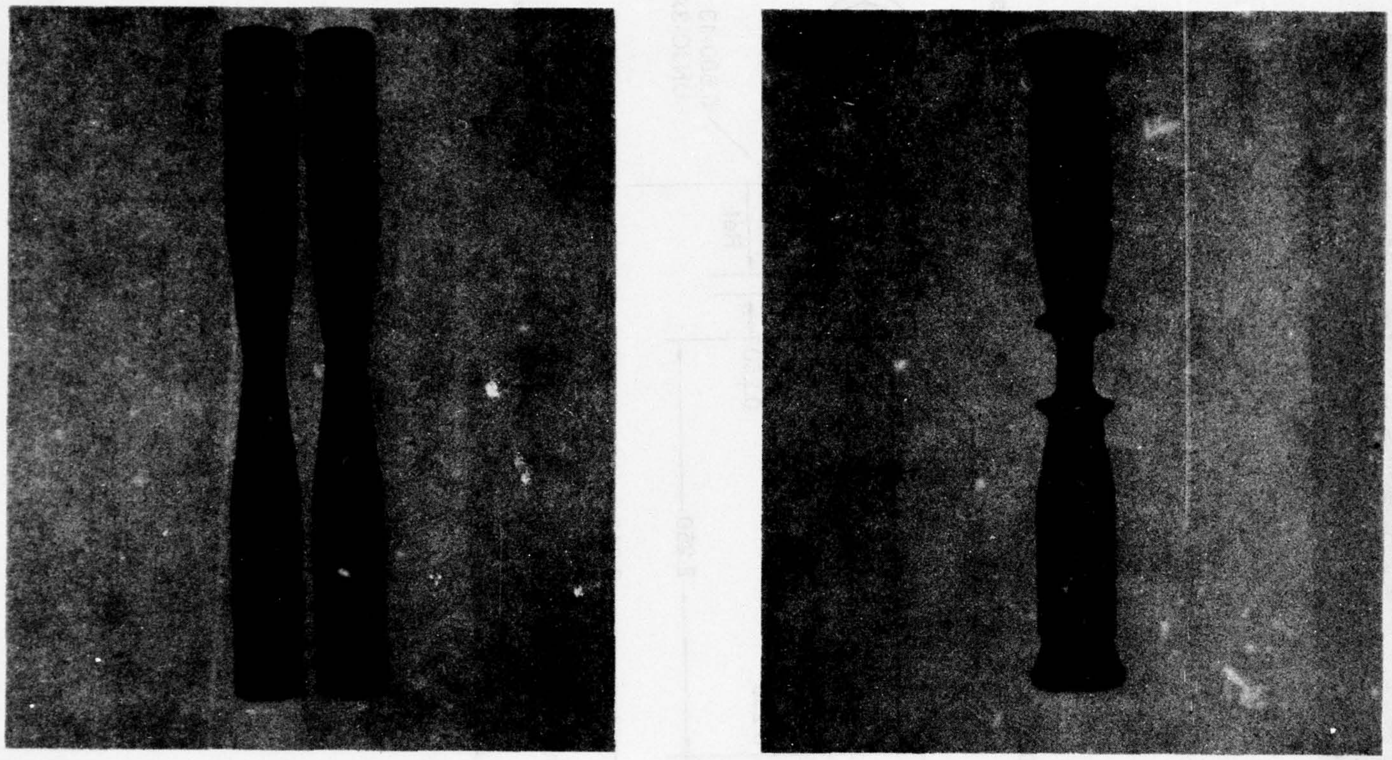
The CC IN 100 creep, tensile, and HCF specimens were machined by conventional grinding techniques. The CC IN 100 LCF and combined creep/fatigue specimens plus all MAR-M200 + Hf specimens were machined by electrochemical grinding (ECG). This machining process offered several advantages over conventional machining including decreased scrap rate, increased uniformity between test specimens, and elimination of machining induced stresses in the specimen gage section. Considering these advantages, it was anticipated that ECG machined test specimens would yield more uniform test data than would be obtained with conventionally machined specimens.

PROPERTIES OF CAST TEST BARS

Prior to commencement of the thermal rejuvenation evaluations, virgin specimens were tested for conformance to the PWA 658 and PWA 1422 specifications for mechanical properties. Accordingly, the CC IN 100 bars were heat treated at the standard 1975°F/8 hr-AC + 1600°F/12 hr-AC while the DS MAR-M200 + Hf bars were heat treated at 2200°F/2 hr-AC + 1975°F/4 hr-AC + 1600°F/32 hr-AC. Mechanical property tests performed with CC IN 100 included 1400°F/85 ksi creep-rupture, 1800°F/29 ksi stress-rupture, and room temperature tensile while those performed with MAR-M200 + Hf included 1400°F/100 ksi creep, 1800°F/32 ksi creep-stress-rupture and room temperature tensile. The results of these CC IN 100 and DS MAR-M200 + Hf tests are tabulated in Tables 24 and 25, respectively, along with the values required by their respective P&WA specifications.

Inspection of the CC IN 100 test results in Table 24 indicates that mechanical properties of these castings were well above those required by the PWA 658 specification. In particular, the 1400°F/85 ksi rupture life was 764.2 hr compared to the 23 hr minimum requirement.

DS MAR-M200 + Hf test results, shown in Table 25, were typical for this alloy with the exception of room temperature tensile which failed at the low end of the ductility range (6.0% vs the normal 5.0% to 13.0%). An additional specimen was tested and confirmed the low room temperature ductility of this heat of material.

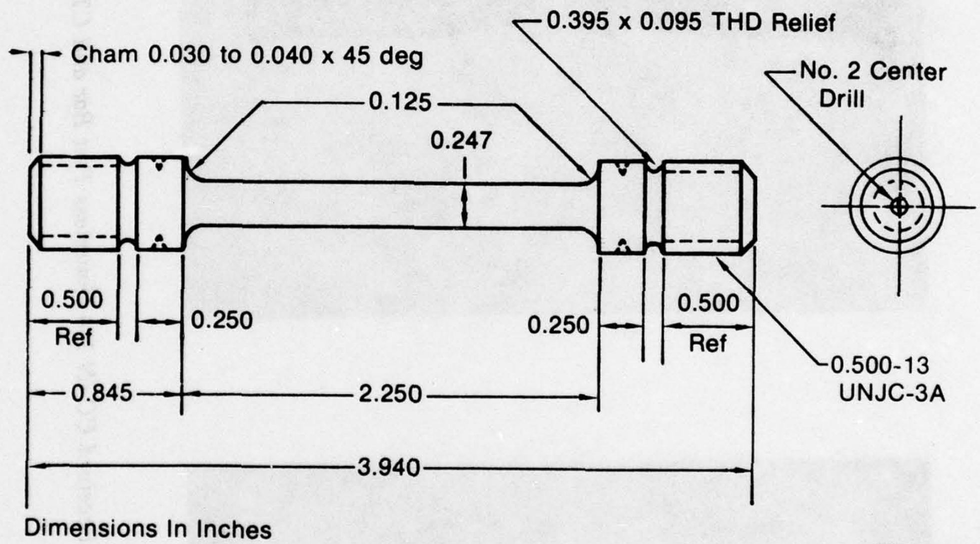


FD 120047

Figure 52. Typical Grain Pattern of As-Received CC IN 100 Hourglass Test Bar and CTS LCF Bar

FD 120048

Figure 53. Typical Grain Pattern of DS MAR-M200 + Hf Par Bar



FD 114849

Figure 54. CC IN 100 Creep and Tensile Specimen

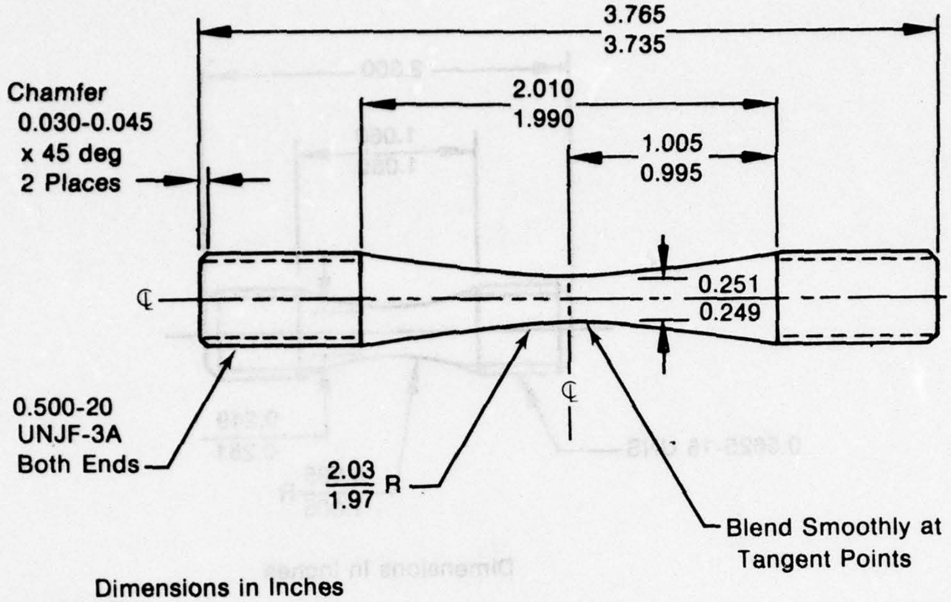


Figure 55. IN 100 Creep and Tensile Specimen

FD 120045

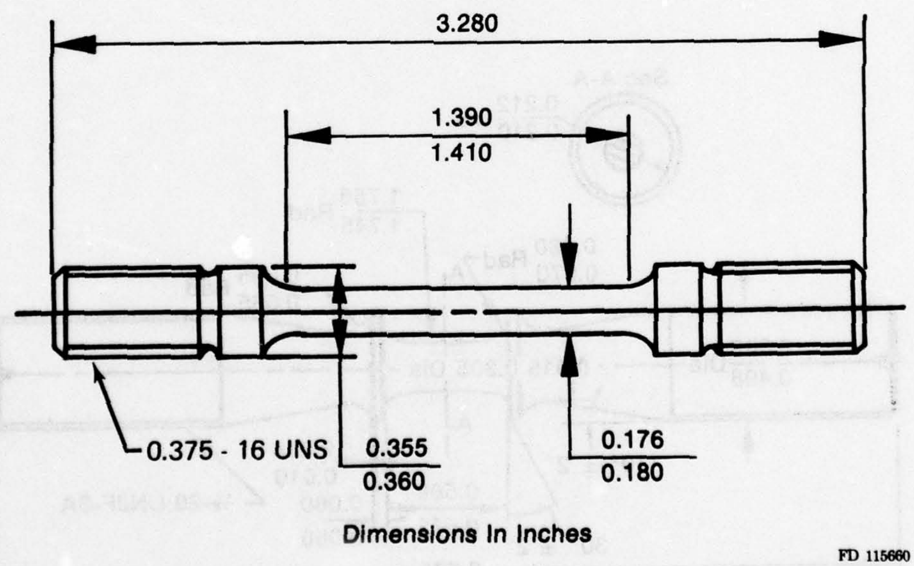


Figure 56. DS MAR-M200 + Hf Creep Specimen

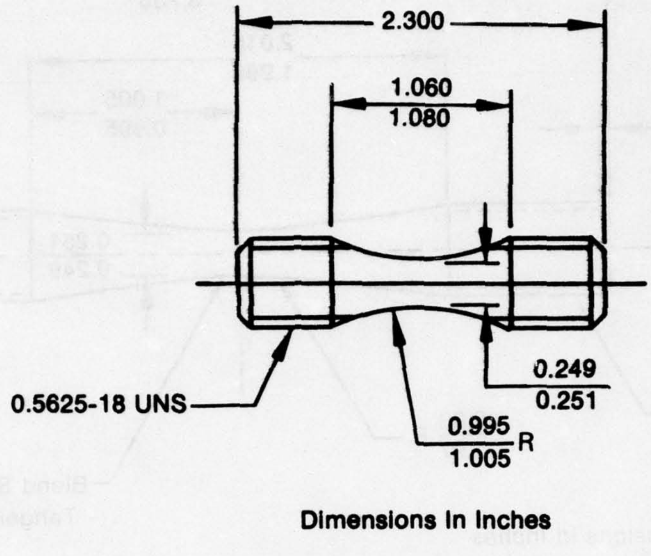


Figure 57. DS MAR-M200 + Hf Axial High-Cycle Fatigue Specimen

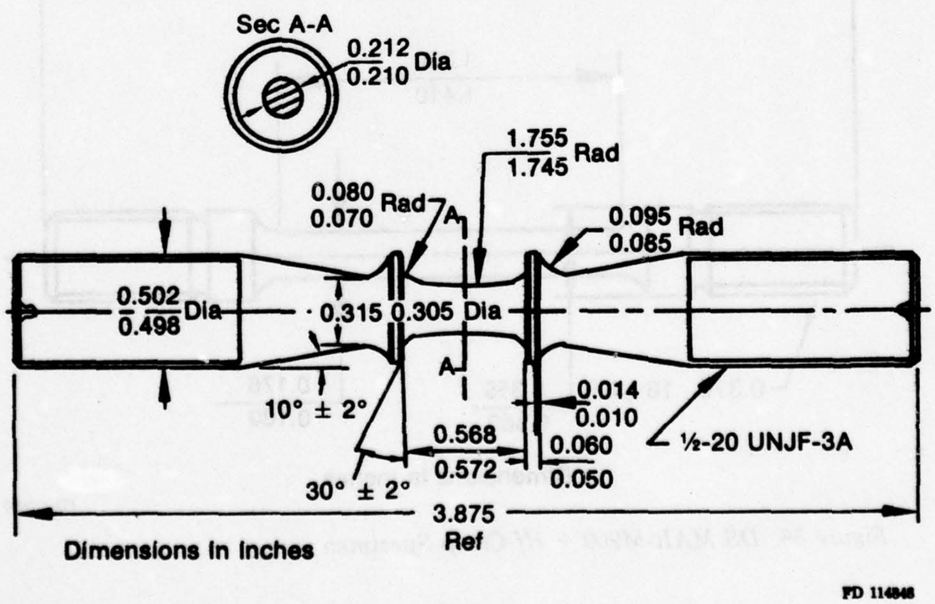


Figure 58. Constant Strain LCF Specimen

AD-A077 527 PRATT AND WHITNEY AIRCRAFT GROUP WEST PALM BEACH FL G--ETC F/G 21/5
REJUVENATION OF TURBINE BLADE MATERIAL BY THERMAL TREATMENT.(U)
JUL 79 M D ROSS, G T BENNETT, D C STEWART F33615-76-C-5208

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TABLE 22. CHEMICAL ANALYSIS AND REQUIREMENTS, PWA 658 MASTER HEAT RU-362

Element	*Master Heat RU-362*	*PWA 658 Specification Requirements*	
		min	*max*
Carbon	0.17	0.15	0.20
Manganese	<0.10	—	0.20
Silicon	<0.10	—	0.20
Phosphorus	—	—	0.015
Sulfur	0.0015	—	0.015
Chromium	9.02	8.00	11.00
Cobalt	14.28	13.00	17.00
Molybdenum	2.95	2.00	4.00
Titanium	4.60	4.50	5.00
Aluminum	5.47	5.00	6.00
Aluminum + Titanium	10.07	10.00	11.00
Boron	0.014	0.01	0.02
Vanadium	0.88	0.70	1.20
Zirconium	0.06	0.03	0.09
Iron	0.14	—	0.30
Lead	1.0 ppm	—	0.0005 (5 ppm)
Bismuth	<0.3 ppm	—	0.00005 (0.5 ppm)
Selenium (3.2.1)	0.5 ppm	—	0.0003 (3 ppm)
Tellurium (3.2.1)	<0.5 ppm	to be reported	
Thalium (3.2.1)	<0.5 ppm	to be reported	
Nickel	remainder	remainder	

TABLE 23. CHEMICAL ANALYSIS AND PWA 1422 REQUIREMENTS, MAR-M200 + Hf MASTER HEAT S-718

Element	*Master Heat S-718*	*PWA 1422 Specifications Requirements*	
		min	*max*
Carbon*	0.16	0.08	0.14
Manganese	<0.02	—	0.20
Phosphorus	<0.015	—	0.015
Sulfur	0.005	—	0.015
Silicon	<0.05	—	0.20
Chromium	8.79	8.00	10.00
Cobalt	9.72	9.00	11.00
Tungsten	11.72	11.50	12.50
Columbium	0.95	0.75	1.25
Titanium	1.93	1.75	2.25
Aluminum	4.84	4.75	5.25
Hafnium*	1.04	1.50	2.50
Boron	0.014	0.010	0.020
Zirconium	0.03	—	0.20
Iron	<0.05	—	0.35
Copper	<0.02	—	0.10
Bismuth	<0.0 ppm	—	0.00005 (0.5 ppm)
Lead	<1.0 ppm	—	0.0005 (5 ppm)
Selenium	<0.5 ppm	—	0.0003 (3 ppm)
Tellurium	<0.5 ppm	to be reported	
Thallium	<0.5 ppm	to be reported	
Nickel	remainder	remainder	

*Out of Spec High Carbon, Low Hafnium

TABLE 24. MECHANICAL PROPERTIES OF CC IN 100 TEST BARS COMPARED TO PWA 658 SPECIFICATION REQUIREMENTS

Test	*Yield Strength (ksi)*	*Tensile Strength (ksi)*	*Rupture Life (hr)*	*Elongation (%)*
Test Bars:				
RT Tensile	118.1	141.2		
1800°F/29 ksi			44.5	9.9
1400°F/85 ksi			764.2	*4.49
PWA 658 Spec Requirements:				
RT Tensile	105	115		
1800°F/29 ksi			23(min)	4
1400°F/85 ksi			23(min)	*2

*Last creep measurement within 2 hours of failure

TABLE 25. MECHANICAL PROPERTIES OF DS MAR-M200 + Hf TEST BARS COMPARED TO PWA 1422 SPECIFICATION REQUIREMENTS

Test	*Yield Stength (ksi)*	*Tensile Strength (ksi)*	*Rupture Life (hr)*	*Elongation (%)*
Test Bars:				
RT Tensile	124.0	142.1		6.0
RT Tensile	123.0	128.3		6.0
1800°F/32 ksi			42.5	20.5 (1.8 in 20 hr)
1400°F/100 ksi			107.0 (disc)	3.2
PWA 1422 Spec Requirements:				
RT Tensile	130.0	150.0		5 to 13
1800°F/32 ksi			32.0 (min)	10 (2% max in 20 hr)
1400°F/100 ksi			48.0 (min)	4% max in 48 hr

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